Feasibility for Anaerobic Digestion Treatment in Seychelles

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Acronyms

AD	Anaerobic Digestion
BioLNG	Biomethane Liquified Natural Gas (liquid RNG)
BOD	Biochemical Oxygen Demand
CHP	Combined Heat & Power (plant)
CNG	Compressed Natural Gas
COD	Chemical Oxygen Demand
COI	Commission de L'ocean Indien
CO2	Carbon dioxide gas
CSTR	Continually Stirred Tank Reactor
DAF	Dissolved Air Flotation
DO	Dissolved Oxygen
DS(C)	Dry Solid (Content)
FM	Food to Microorganism ratio
e	Exponential function
GHG	Green House Gas
H2S	Hydrogen Sulfide
HRT	Hydraulic Retention Time
IOT	Indian Ocean Tuna Ltd Company
Kwh	Kilowatt hour
LEL	Lower Explosion Limit
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MJ	MegaJoule
MRF	Materials Recycling Facility
OLR	Organic Loading Rate
PET	Polyethylene Terephthalate
PSI	Pounds per Square Inch
Q	Daily flow rate or wastewater
RNG	Renewable Natural Gas
R&I	Research & Innovation
S	Substrate Concentration (VS/volume)
SCR	Seychelles Rupee
TS	Total Solids (fraction of waste that is devoid of water)
TWENex	Transformation of Waste towards an Energy Nexus project
UEL	Upper Explosion Limit
V	Volume (in m^3)
VFA	Volatile Fatty Acids
VS	Volatile solids (fraction of dry waste that decompose)

1. Introduction

1.1 About the TWENex Project

The “Transformation of the waste sector towards a waste-energy nexus in the Southwest Indian Ocean region (TWENex)” project aims to boost national innovation systems and strengthen research and innovation capacities by supporting the research community. The project is currently being implemented in four Small Island Developing States (SIDS) of the Indian Ocean. The TWENex project is facilitating the development of a waste-to-energy ecosystem within the Indian Ocean region, while recognising and addressing local and sub-local specificities. In partnership with focal points, multipliers and other local and regional organisations, the activities being carried out include:

- Collection and update of relevant data for analysis and informed decision making on waste management.
- Strengthening interactions between public and private actors to identify areas of collaboration for business development and project implementation.
- Implementing R&I demonstration projects and pilot projects.
- Development of technical and business models for technology transfer.
- Transfer, scaling and replication of the models.

1.2 Overview of Anaerobic Digestion

Anaerobic digestion is a method of biological waste treatment where the waste is decomposed in an oxygen free environment for the purpose of generating biogas and at same time significantly reducing the environmental impact of such waste. Biogas is a renewable energy source consisting of a mixture of methane and carbon dioxide which is used to generate electricity through combustion for large scale systems or as a fuel source for cooking in smaller plants. Below are some key AD terms used.

Feedstock refers to the material that is being digested. This is any organic waste such as sewage, cattle manure, fish waste etc.

Total solids (TS) of any feedstock are the dry fraction without water. As can be expected the higher the moisture content the less organic solids you are adding to the digester. Therefore it is important to know when one weigh out the feedstock what is the actual dry organic matter and what constitute water. This is found by drying a sample of the feedstock above 105 C for 24 hours and weighing the difference.

Volatile solids (VS) are the biodegradable organic fraction of the feedstock. The % VS is found by incineration of the feedstock at 550C for at least 2.5 hours in a muffle furnace to burn out all organic compounds. The remaining fraction will be inorganic compounds that are non-digestible. The VS will be equal to the percentage mass loss throughout such process.

1.2.1 Phases of anaerobic decomposition

Anaerobic Digestion itself occurs in four-stages, being

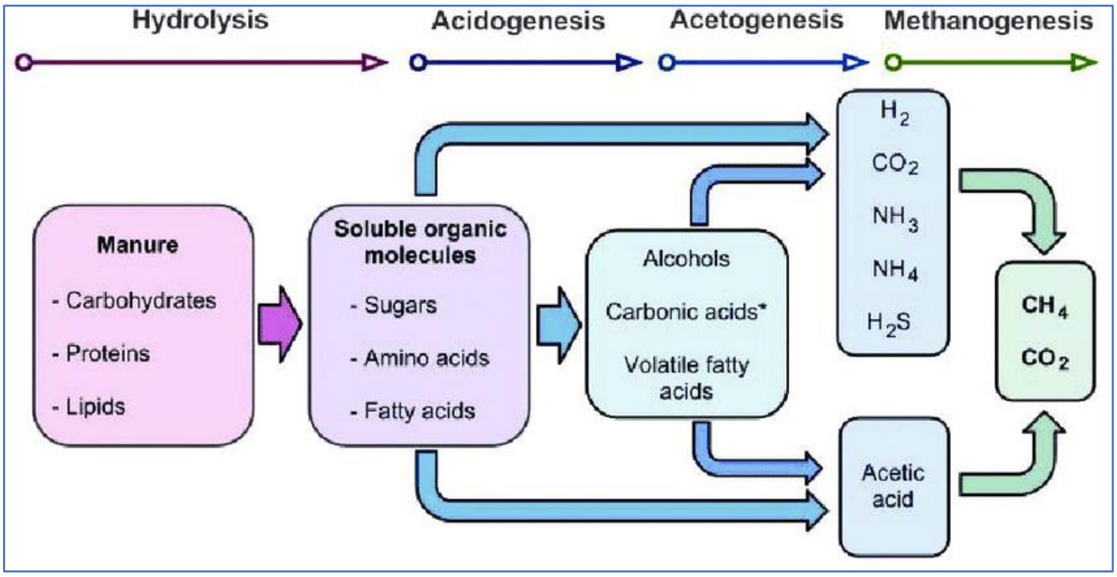
1) Hydrolysis: where the polymeric carbohydrate and protein compounds are broken into smaller chained monomeric compounds such as amino acids, sugars, and fatty acids

2**) Acidogenesis:** where the above compounds are oxidized to volatile fatty acids (C3-C6 acids), alcohols, aldehydes and carboxylic acids,

3) Acetogenesis: where the above are cleaved into two carbon acetic acid with production of carbon dioxide, ammonia, hydrogen and hydrogen sulfide and finally

4) Methanogenesis: where the acetic acids are further broken down into methane and carbon dioxide. The temperature at which the process is allowed to occur determines the rate or decomposition as well as the types of bacteria involved.

Figure 1: Phases of digestion of biowaste under anaerobic condition



1.2.2 Wet vs Dry systems & hydraulics

Wet vs dry fermentation systems: The Ad process in categorised depending on the percentage total solids (TS). In wet fermentation systems the total solids is between 2%-10%, while the dry fermentation system handles >30. It is recommended that slurry be kept at 7-9% for big reactors in order to facilitate pumping and mixing of the feedstock and digestate.

Plug Flow hydraulics: The hydraulics of AD is similar to wastewater treatment. In plug flow system, the feedstock enters one end and pushes the digestate out the other end. The organic matter moves as a block through the system digesting as it goes along with most digested in front and less digested at the back. There are no mixing only agitators that work to push the waste forward.

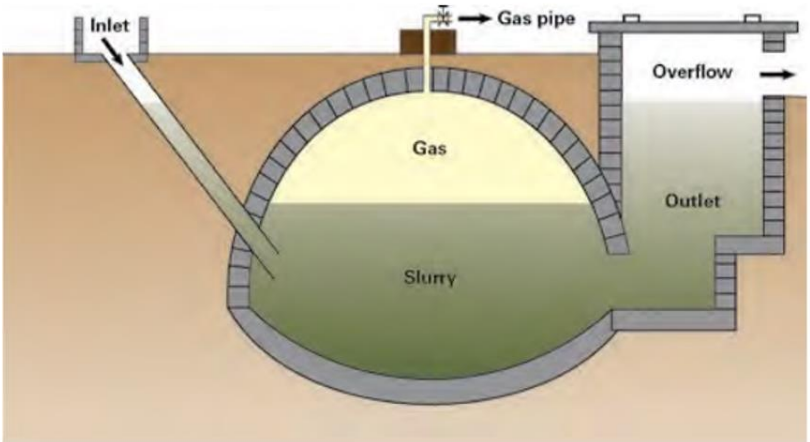
Continuous Stirred Reactor (CSTR): In CSTR, the feedstock is mixed thoroughly by mixers in the reactor so that at any time the rate of decomposition is similar everywhere in the tank. CSTR allows for faster degradation and biogas recovery but requires an input of energy.

1.2.3 Small to medium AD plants

Small to medium AD plants are usually of the plug flow types and are based on three main designs: 1. Fixed dome, 2) floating dome and 3) membrane.

Fixed dome: In the fixed dome also known as Chinese fix dome, the construction is made with bricks and motar and the structure is usually placed underground with only inlet and outlet accessible. This is useful since it facilitates loading and any accidents of the reactor will be safely contained. The disadvantage is that acids produced can eat away at the concrete and over time cracks can appear leading to loss of gas.

Figure 2: Chinese fixed dome digester



Floating dome: Also called Indian floating dome, consists of a fiberglass reinforced plastic tank for the reactor and another smaller reactor is inverted inside the tank and allowed to float up as the gas accumulates. A hose from the floating gas collector brings the gas to its point of use. This gives a visual cue of the amount of gas generated. The floating dome can have mechanism that allow for some mixing by rotating the dome hence agitating the reactor.

Figure 3: Indian floating dome design

Membrane: Also known as Taiwan model, the digestor is a flexible polyethene membrane which is longitudinal to allow for batch kinetics. Waste enters one end and pushes the digestate out the other end in a linear model. Gas builds inside the membrane which gets expanded. This also provides visual cue of gas being generated and as with floating dome, the membrane can be weighed down with tyres or other materials to increase gas pressure.

Figure 4: Membrane digester

1.2.4 Large scale AD systems

Large AD systems are CSTR types and constructed out of stainless steel or thick glass enamelled metal sheets joined with stainless steel bolts. These tanks can be high (12m). Stirring is very important here as not only does it change the hydraulics to improve degradation but also prevent high hydrostatic pressure (>4m height) to inhibit methane production. These systems are maintained at a fixed temperature which may be mesophilic or thermophilic (see 1.2.6). The CSTR ensures that bacteria remain in suspension with the food and are spread throughout the volume of the tank. Usually, biogas is stored in other vessel with a membrane on top that are inflated with gas. In Seychelles one such industrial system exists at the Indian Ocean Tuna Ltd for the anaerobic digestion of fish waste (see annex2). This plant's primary focus is wastewater treatment and dealing with the solids coming out of the process. Therefore, the biogas generated is not stored but rather flared as a by-product of the process. We can see that this plant is near 14m heigh with access stairs for operator to be able to undertake inspection and repairs of equipment.

1.2.5 Feedstock

Feedstock (also known as substrate) is the most important parameter for an AD plant and must be carefully assessed for the design. Leaves and yard trimmings are not well-suited for AD as for composting because of low biogas yields, as they are generally resistant to digestion because of high lignocellulosic materials (although grass may digest very well if it is separated). If primarily leaves and yard trimmings are collected, the investment in digestion equipment will generally be too high to justify the returns from biogas and other products, no matter what the incentives.

Food wastes from residential, commercial and institutional sources, fats, oils and grease, and food processing wastes, have much higher biogas yields and digest more rapidly and completely in a digester than leaves and yard trimmings. Whereas yard trimmings typically produce less than 30 cubic meters of biogas per metric ton of as-received raw feedstock (assuming 60% methane by volume at standard conditions of 20°C and 1 atmosphere pressure), food waste typically produces 100 cubic meters of biogas per metric ton received. The highest energy food waste feedstocks can produce five times this much biogas with much less preprocessing and other costs than for leaves and yard trimmings

1.2.6 Process parameters & control

Temperature: There are three primary temperature ranges for AD namely psychrophilic (10-20 C)., mesophilic (20-40 C) and thermophilic (40-60 C). AD can occur in any of these ranges but mesophilic and thermophilic are preferred as they lead to faster degradation and higher gas formation. Thermophilic is superior however high ammonium levels can be problematic as the high temperature shifts the ammonia equilibrium toward production of a higher level which inhibits AD. An option to reduce high ammonia during thermophilic operation is to mix the food waste with other substrates such as park and garden waste and/or water to dilute. However, this approach increases the operating cost for the plant and reduces the nutrient concentration in the digestate. Another strategy is to lower the temperature to mesophilic level, which in Europe would require an external hygienisation unit as the temperature is not enough to kill pathogenic bacteria to meet laws for digestate use.

Organic loading rate: The organic loading rate (OLR) is the amount of volatile solids added per day as a function of the reactor volume. A bigger volume can take a higher feeding rate. The OLR depends on the hydraulics, e.g. the digestor can have a stirrer to keep bacteria and substrate in suspension or not. For unstirred reactor an OLR of less than $2kg/m^3.d$ is recommended while for stirred reactors it can go up to $10kg/m^3.d$. This is because as new substrate enters, the acid forming bacteria quickly breaks them into volatile acids causing a decrease of pH in the digestor. Since the methanogenic bacteria are pH sensitive (6.7-7.4) this can inhibit the gas producing bacteria.

Hydraulic retention time: A key design parameter is the residence time of the substrate in the digestor also known as the Hydraulic retention time (HRT). The residence time allows for complete degradation of the organic material so that as it exits it does not have a strong oxygen demand and has undergone maximum degradation. The Hydraulic retention time is a function of the reactor volume and the influent flow rate. The higher the flow rate of substrate the bigger the reactor needs to be to allow for complete digestion. The typical retention time for psychrophilic bacteria is 40-100 days, mesophilic bacteria is 25-40 days, and 15-25 days for thermophilic bacteria.

Ammonia: Ammonia level is a strong impact parameter for biogas processes. Free ammonia and ammonium ions ($NH4^+$) are released during degradation of proteins. The level of ammonium-nitrogen in the process depends on the substrate composition and on the degree of mineralisation of the process i.e. the proportion of organic material converted to methane. A high content of ammonium provides the process with alkalinity and increases the value of the digestate as a fertilising agent and can also contribute with a hygiensation effect however it causes acetogenesis inhibition causing accumulation of volatile fatty acids (VFA), decreasing methane yields and sometimes even process failure[6]. Ammonia concentration of 4.92 and 5.77 g/l causes a drop in methane production by as much as 39% and 64% with 100% inhibition in the range of 8–13 g/l[8].

Mixing: As stated, mixing is done by mechanical stirrers to keep the bacteria in suspension. This ensures that they are always in contact with food which in normal cases will settle at the bottom. It allows for a stirred reactor to operate at a higher OLR.

Carbon to Nitrogen(C:N): The C:N ratio is the ration of carbon and nitrogen in the feedstock. Literature site that this should be the same as for composting namely within a range (30:1). The microorganisms require nitrogen for protein synthesis however too much can result in formation of ammonia and change the pH.

pH: Measure of the acidity and basicity of a solution. The pH of AD process needs to be in a stable range of 6.7 -7.4 otherwise the process is inhibited.

Volatile Fatty Acids (VFA): VFA are short chain fatty acids (carboxylic acids) that are produced during the process of anaerobic digestion. The most common VFAs are acetic (C2), propionic (C3), isobutyric, butyric (C4), isovaleric, valeric (C5), and caproic (C6) acids. Acetic acid is used to measure VFA in the laboratory and it has to remain below 2g acetate / litre for efficient fermentation [14]. High OLR values can lead to pH drop due to the fast generation of VFAs and its build up means that the AD process is being negatively affected and methanogenic bacteria inhibited. Low VFA also points to inhibition of acidogenesis due to inhibitory compounds. The inhibition of the process is characterized by a strong decrease of the most abundant VFA namely acetic acid.

Inhibitory compounds: Different compounds are responsible for acidogenic inhibition. Potassium (K^+), Sodium (Na^+), clorophenols and heavy metals (Cu > Zn > Cr > Cd > Ni > Pb) are toxic for acidogenesis [10]. Sodium in particular is relevant for some waste stream in Seychelles e.g. fish waste. Sodium affects the specific growth rate of microorganisms because it plays a role in the formation of adenosine triphosphate (ATP) and NADH oxidation. Although it is beneficial at minor concentrations ($<1\ g\ L^{-1}\ Na^+$), higher amounts affect growth and methanogenic inhibition can be achieved at Na^+ values ranging 3.5–5.5 g L^{-1}. [9]

1.3 Theoretical biomethane production

1.3.1 Modified Gompertz

As the feedstock is loaded, the degradation process starts and gas production begins. The AD process is relatively slow so sufficient time must be given and we must understand the volume of gas produced over time. The cumulative biogas production volume (V) mirrors bacterial grown rate which is a sigmoid function known as the modified Gompertz equation. For biogas production we use the modified Gompertz equation as given below.

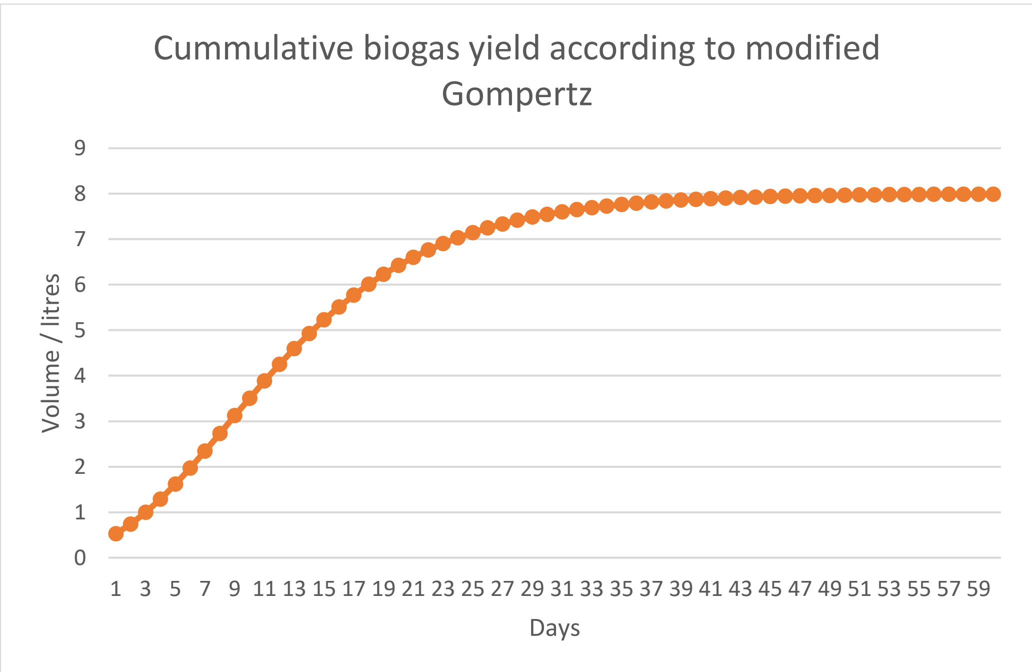
$$V = H_m e^{-e^{\left(\frac{Rm}{Hm}\right)*e*(\lambda-t)+1)}}$$

where V is the cumulative volume of gas produced over time t. H_m is the maximum gas production and R_m is the maximum gas production rate and λ is the lag phase (residence time). These constants are found experimentally for particular feedstock. However, we can calculate roughly the gas production rate or methane yield based on chemical oxygen demand (COD) which is the demand for oxygen by the oxidation of organic matter. The reaction of methane with oxygen is given by

$$CH_4 + 2O_2 \rightarrow CO_2 + H_2O$$

We see 2 moles of oxygen (64g) is required per mole of methane (16g). So **each mole of methane produced is equivalent to removal of 64g of COD from the organic matter**. As a gas at standard atmospheric pressure, 1 mole methane occupy 25 litres. Therefore 64g COD occupy 25 liters which by simple calculation gives the gas production rate at 0.39 litres/gCOD. According to this, the maximum gas yield for a 40g of feedstock is 15.6 litres and so the cumulative gas over time according to the above equation is given in figure 5 for $V = 15.6e^{-e^{\left(\frac{0.39}{15.6}\right)*e*(1-t)+1)}}$.

Figure 5: Estimated biogas volume over time in days



1.3.2 First order kinetics

We can also make a prediction of gas yield by considering a different approximation, namely first order kinetics. First order kinetics assumes that the decomposition of organic matter under anaerobic conditions is proportional to the organic matter substrate. This is represented by

$$\frac{dS}{dt} = -kS$$

Where S is the substrate concentration in (g/ml) and k is the degradation rate constant. Integrating this first order differential equation, we obtain $S_t = S_0 e^{-kt}$. S_0 is the initial substrate concentration and S_t.is the substrate concentration at any time t.

Now we consider that the difference in substrate amount at any given time in grams is proportional to the gas yield Y_t. Therefore $(S_0 - S)V \propto Y_t$. Where V is the volume of the reactor.

Substituting terms, and removing proportionality sign we have

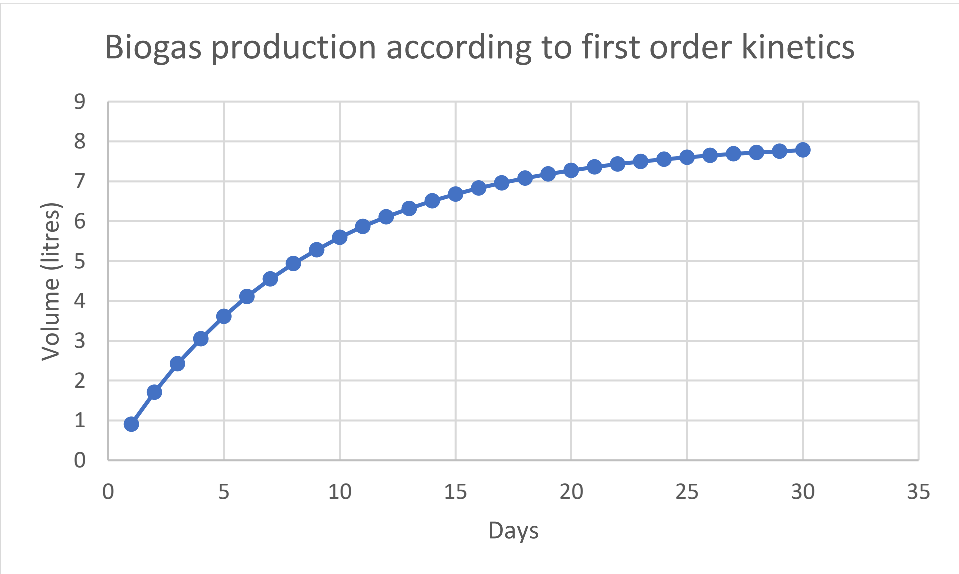
$$(1 - e^{-kt})VS_0 = \rho Y_t.$$

Now we assume a biogas production constant μ where $\rho = \frac{1}{\mu}$.

$$Y_t = \mu(1 - e^{-kt})VS_0$$

We can use the above equation to estimate the methane yield (Y_t) in litres at any given time in days for the pre-laboratory studies. If we take the above assumption, we would get the theoretical methane cumulative production as per figure 6 below.

Figure 6: Biogas production according to first order kinetics



We can see that the first order kinetics leads to faster rate of gas production compared to the Gompertz model in figure 5. In the small scale investigation (section 2.5), we try to find which model work for food waste in Seychelles.

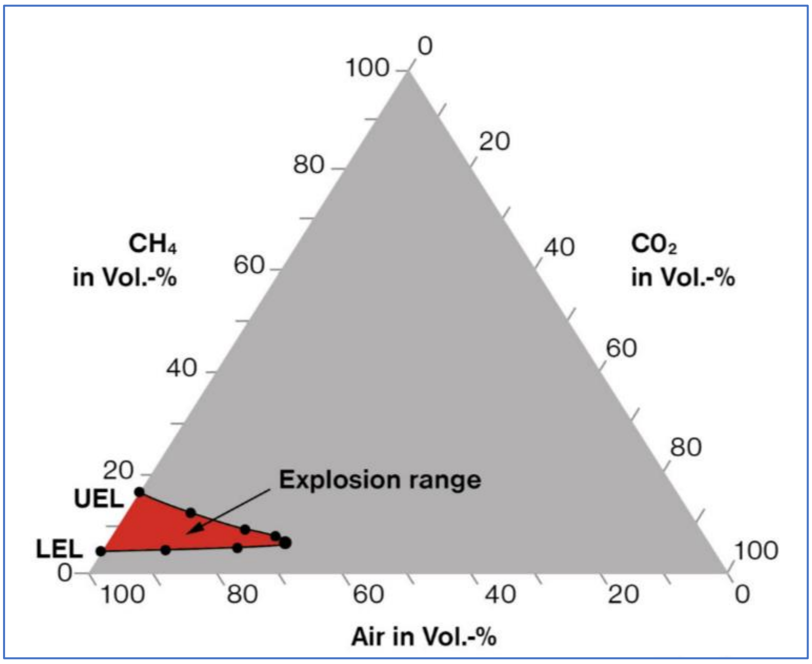
1.4 Safety consideration

Biogas is composed of principally two gasses namely carbon dioxide and methane. Methane is a flammable gas and like most of these gasses it can explode under certain conditions. The condition for explosion is that 1) there must be a certain range of methane to air ratio and 2) a source of ignition.

1.4.1 Methane to air ratio

Figure 7 shows the biogas pyramid with methane concentration on the left face and carbon dioxide concentration on the right face. The bottom face is the air concentration. We see that conditions for explosion exist in the red zone bounded by an Upper Explosion Limit (UEL); being the highest concentration of methane that can explode (18%), the Lower Explosion Limit (LEL); being the lowest concentration of methane that can explode and the air concentration.

Figure 7: Explosive limit of methane and air



It is important to re-iterate that **two** conditions need to exist at the same time for explosion (namely right ratio and ignition source). Therefore, it is important to ensure that excessive air is not introduced into the reactor. During startup the system will have air that needs to be purged. This can be done by allowing biogas accumulated to be vented for the first two gas accumulation thereby building up the methane concentration past the LEL and UEL. Other technique used in big plants is to purge the air with an inert gas like nitrogen so that anoxic condition is maintained immediately.

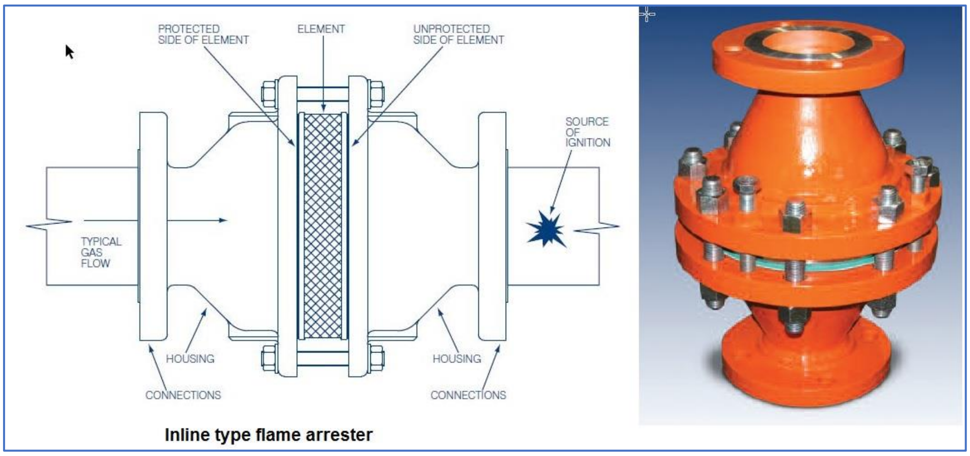
A gas meter can be used to verify that the concentrations are in the safe limit. The gas meter can also be installed directly in the line for active monitoring of gas concentrations.

1.4.2 Flame arresters

Flame arresters are safety devices whose principal purpose is to prevent a flame entering or leaving a pipe or vessel or to prevent it traveling further down a pipe. In many cases it is used in conjunction with other components to create a safety system. Failure to stop a flame can result in catastrophic damage to equipment, loss of production, injury to people and even loss of life and potentially large litigation costs. Although not common on small AD plants, large AD plants use flame arresters to prevent explosion and there is an EU standard developed for such devices.

Inline arresters: The principal design of inline arresters consists of a small metal mesh (element) inside an expanded volume which prevents a flame from passing through to the other side. These are placed before igniters e.g. to flare the gas or injection into a generator for production of electricity. Figure 8 shows the details of an inline flame arrester.

Figure 8: Example of an inline flame arrester



Hydraulic arrester: These are made of a liquid (usually water) allowing the gas to bubble through it but it is not possible for flame to travel through the water and into the gas inlet port. Hydraulic arresters are cheap and commonly used for small AD plant as it not only protects the digester from explosion but also provides a visual cue of gas production.

The photo on the left shows a hydraulic arrester used in the small scale, comprising of a 5 litre bottle of water. The inlet gas tube was placed 10cm under the surface of water and the outlet is above water. A small volume of air above the water line exists. As gas moves it bubbles through the liquid and exists the other tube. If there is back flame it will reach the small gas pocket and be extinguished. This setup also cleans the biogas of contaminants.

1.4.3 Pressure relieve valve

There is possibility of too much gas pressure in the digestor or pipes that can lead to an pressure explosion especially if there are blockages. As can be expected, plants are equipped with pressure relief valve that release excess biogas should it react a particular pressure. These can be mounted on the digester and or the piping to the gas collector and or on the gas collector. A simple and cheap way to include a pressure relief valve in small DIY digesters is to use a 1.5 PET bottle filled with water to which a clear tube is inserted and connected to the gas line (figure 9). A simple water manometer can also function as a biogas pressure gauge as shown below. These are incorporated in the gas line by a T and uses hydrostatic pressure of water to measure the dynamic gas pressure. As pressure builds up, it pushes the water column and the height in cm is equal to the pressure in milibar. When it exceeds the maximum pressure as determined by the water level, it bubbles out and is vented to the atmosphere. Figure 10 shows a professional spring-loaded relief valve used in large plant.

Figure 9: DIY pressure relief valve and pressure gauge: Adapted from [13]

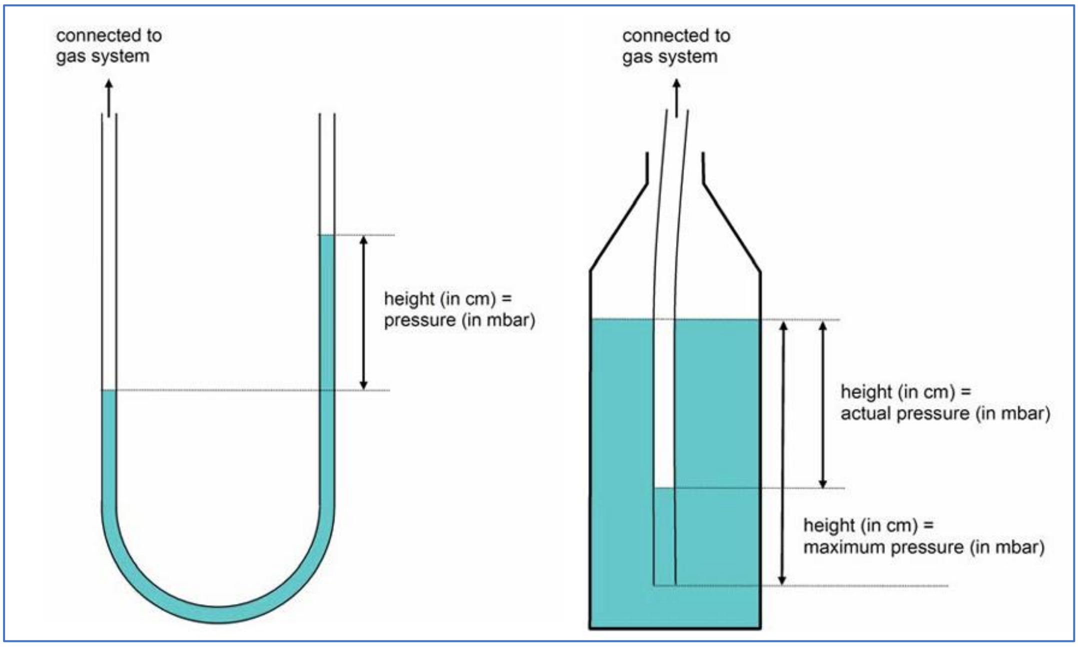
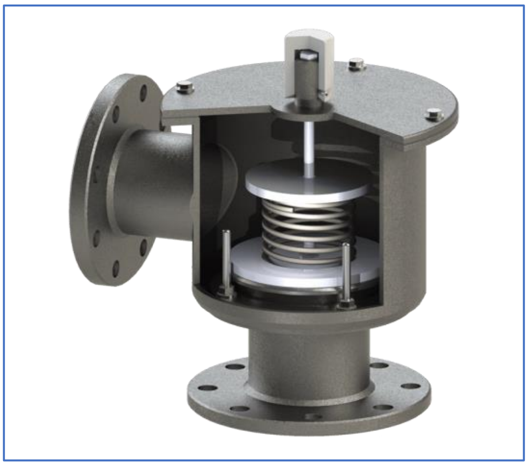


Figure 10: Spring loaded pressure relief valve



1.5 Gas scrubbing

Biogas not only contain methane and carbon dioxide but also trace amount of hydrogen sulfide and volatile organic compounds.

1.5.1 Removal of Hydrogen Sulfide

This contaminant gas comes from the decomposition of sulfur containing amino acids (methionine and cysteine) from proteins. The concentration of hydrogen sulfide in biogas depends on the feedstock but it is usually in the range 0.5% -3% (5000 - 30,000ppm). Hydrogen sulfide is problematic from a number of standpoint;

1. **Corrosion:** This gas is corrosive and reacts with water vapour to give sulfuric acid. The gas and the acid corrodes metal surfaces and destroys equipment such as monitoring instruments, pipes and storage tanks.
2. **Health hazard:** Even in low concentrations, it can cause respiratory problems.
3. **Environmental Impact:** When biogas containing hydrogen sulfide is combusted, the sulfur reacts with oxygen to for sulfur dioxide. This gas is also problematic as an air pollutant and the culprit behind acid rain.

Various techniques are available to remove hydrogen sulfide.

Reaction with Iron salts. The most common scrubbing is the use of iron oxide (see figure 11). Hydrogen sulfide gas reacts with iron oxide to form iron sulfide and water. Iron sulfide is a solid therefore this reaction pulls the sulfur out of the gaseous phase into solid phase thereby cleaning the gas. The reaction is given by

$$3H_2S + Fe_2O_3 \rightarrow Fe_2S_3 + 3H_2O$$

Since the reaction produces water, the gas may need dehumidification before being ignited. It is why biogas scrubbers also include a drying step to remove water. This can be through a cooling tube where water condenses or silica gel to absorb the moisture from the gas. Small plants typically use steel wool to scrub hydrogen sulfide. As the wool oxidizes in the moist environment and turn red, it generates iron oxide to which hydrogen sulfide reacts.

Reaction with water: A very cheap way to remove hydrogen sulfide is to bubble it in water. The gas dissolved in water to form sulfuric acid. Over time, this water needs to be replenished. The method works well with low flows however may not be very effective for higher levels of hydrogen sulfide.

Adsorption by activated carbon: Hydrogen sulfide may also be removed by adsorption on materials such as activated carbon. Activated carbon is often used after a treatment has been carried out with iron oxide to enhance hydrogen sulfide removal. The spent activated carbon cannot be regenerated and has to be replaced. Figure 8 shows a typical scrubber composed of iron oxide pellets, steel wool and desiccants.

Removal by aerobic bacteria: H2S in a gas stream can also be removed by microbiological methods such as fixed film biofilters, bio trickling filter or activated sludge process. The latter involves bubbling the gas stream through gas spargers into an activated sludge tank. Water-soluble H2S is absorbed into the mixed liquor and subsequently degraded by the microorganisms in the liquor [9]. The bubbling method can be easily applied when the activated sludge system is located near the waste gas stream(s). The process can be used to remove H2S in gases that are emitted from anaerobic digesters.

Figure 11: Example of iron oxide biogas scrubber

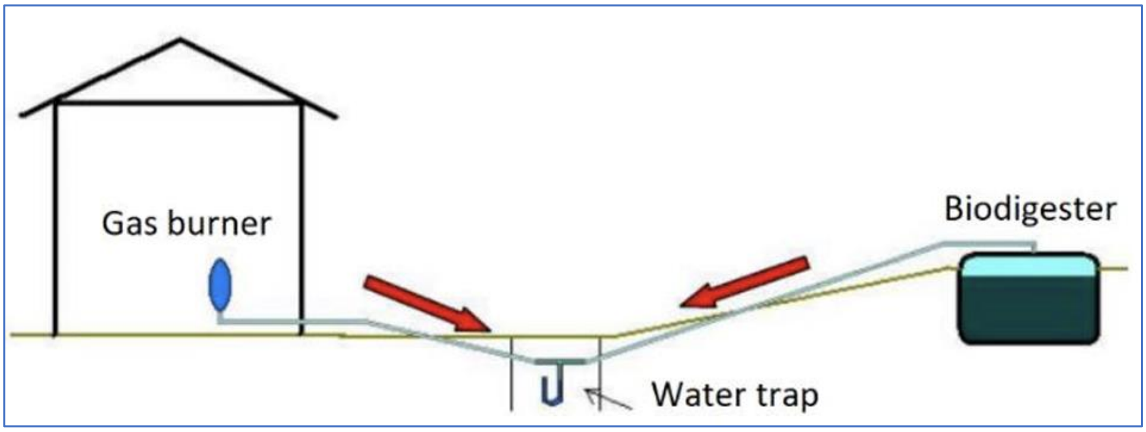
1.5.2 Removal of water vapour

Water vapour is present in biogas since the gas is in contact with water in the digester. Water vapour is likely to condense in the gas pipe which leads to blockages and poor flow. Water vapour also is problematic when the gas is being used in cooker tops as it causes flame sputtering and may even extinguish the flame.

Removal by a desiccant: Water vapour are removed by passing the gas through a dessicant such as silica gel. The advantage is that spent silica gel can be regenerated by drying it out in an oven and available to be reused.

Removal by Condensation: Water is removed by condensation either passive or induced. A condensation trap work by removing water that has been condensed in the pipe (to prevent blockage). For small plants a simple trap can be placed at the low end of the gas pipe where condensed water can flow into the trap and are expelled (figure 12)..

Figure 12: Simple condensation trap (adapted from [12])



There are also condensation traps sold on the market (figure 13) for large plants and the use of cooling to reduce moisture. In figure 12, the large pipes carry gas and the condensation trap have a bottom valve to remove condensed water from the system.

Figure 13: Condensation trap in a large biogas plant

Src: https://www.biogasproducts.co.uk/project/condensate-pots/

1.5.3 Removal of carbon dioxide

Carbon dioxide can be scrubbed out of the biogas stream especially when there is intention to maximise the heating value of the gas or make use of the carbon dioxide. The carbon dioxide may is usually cooled and compressed for use in industrial application. We show here two different carbon dioxide removal systems.

Chemical scrubbing

Small scale plants typically use an alkaline solution of sodium hydroxide (caustic soda) (NaOH) or calcium hydroxide ($Ca(OH)_2$) also known as lime water to remove carbon dioxide. The gas is bubbled inside the solution where carbon dioxide reacts with the base (figure 14). The equation for the reaction is given by

$$CO_{2\,(g)} + 2NaOH_{(aq)} \rightarrow Na_2CO_{3\,(aq)} + H_2O_l$$

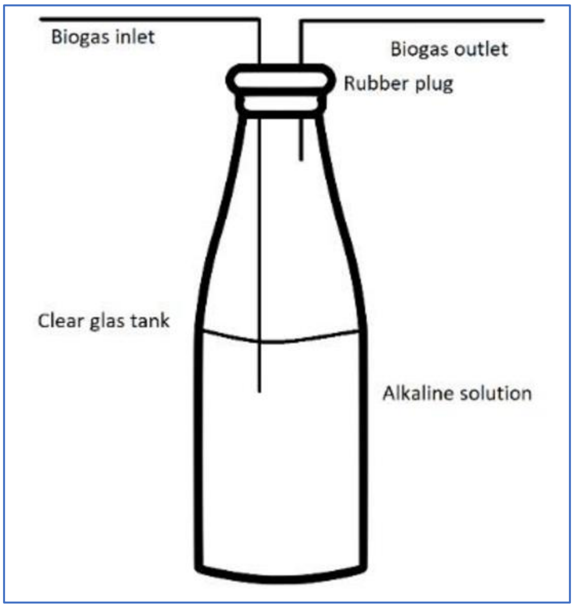
The end result is formation of sodium carbonate which is soluble in water up to 215g per litre. There is no immediate visual confirmation of the scrubbing action which is why calcium hydroxide is sometimes preferred.

In the case of calcium hydroxide, you will remember from high school chemistry that it is the standard laboratory test for carbon dioxide as the end product (calcium carbonate) forms a white precipitate. The equation is given below.

$$CO_{2\,(g)} + Ca(OH)_{2\,(aq)} \rightarrow CaCO_{3\,(s)} + H_2O_l$$

The calcium hydroxide is insoluble in water and comes out as a white precipitate.

Figure 14: Example of a simple CO2 scrubber adapted from [12]

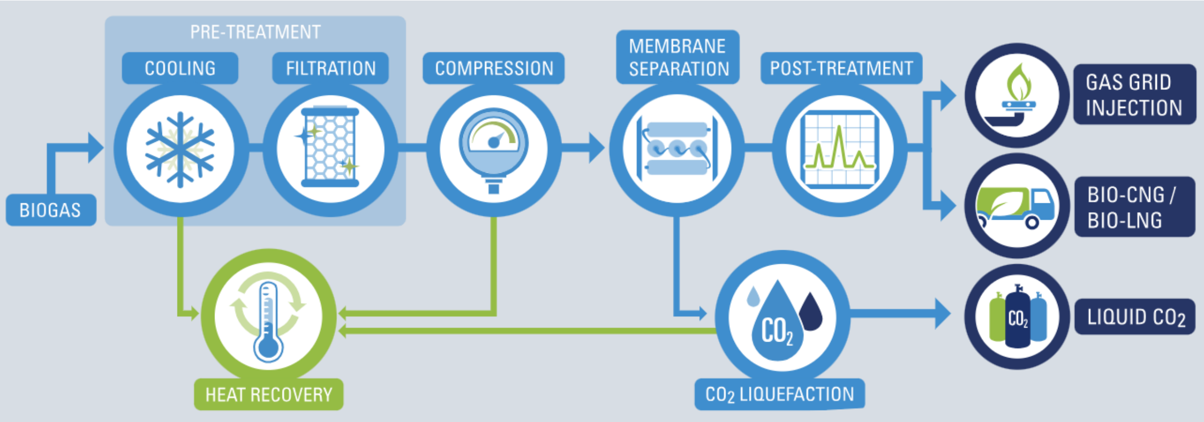


Both methods trap gaseous carbon dioxide in carbonate form which may not be easily accessed without further chemical reaction. The other scrubbing method described below removes carbon dioxide as gas for immediate use.

Membranes:

Recent advances in biogas scrubbing make use of membrane technology (figure 15) to separate carbon dioxide from biogas. In the process below, biogas undergoes pretreatment cooling to remove moisture and passed through 3 filter of activated carbon to remove hydrogen sulphide and volatile organic compounds. It is then compressed and sent through other membrane to separate the carbon dioxide from methane. The carbon dioxide is liquified and sold while the biogas can be injected into the grid for energy or converted into CNG or bioLNG.

Figure 15: Process of separating biogas component by membrane



Src: https://www.bright-renewables.com/technology/biogas-upgrading-membrane/

In figure 16 we see how a collection of these membranes are organised in gas tight metal tubes.

Figure 16: Example pf biogas separating membrane filters

Src: https://www.bright-renewables.com/technology/biogas-upgrading-membrane/

2 Small scale investigations

In chapter 1 we looked at the details of anaerobic digestion and in this chapter we look at two small scale tests that were conducted over the course of two months. One involved assessing the amount of gas produced for a fixed amount of feedstock to determine the kinetics and the other was to test out design element of a continuous flow digester to check design elements being considered for two locally made digesters.

2.1 Kinetics small scale

Based on calculations presented in chapter 1, a 40g feedstock was chosen for gas production in a 12 litre water bottle under first order kinetics. We know from chapter 1 that the (slightly over-estimated) theoretical yield of methane according to first order kinetics is given by $Y_t = \mu(1 - e^{-kt})VS_0$. We looked at literature for food waste[1] where a much lower amount of gas was produced and decided expect a smaller gas production (using gas production constant of 200mg/l). Using our value for feedstock and volume in this equation (table 1), the theoretical production for both models is reproduced in figure 17 and 18.

Table 1: Parameters for small scale batch study

Parameter	Units	Values	
Volume V	l	2.5	Fixed
Substrate	grams	40	Fixed
Substrate concentration S_0	grams/ml	0.016	Fixed
Degradation rate constant K	Day^{-1}	0.12[2]	Assumed
Biogas production constant μ	ml/g	200	Assumed
Cumulative biogas yield Y_t	litres		Calculated

Figure 17: First order biogas yield for food waste

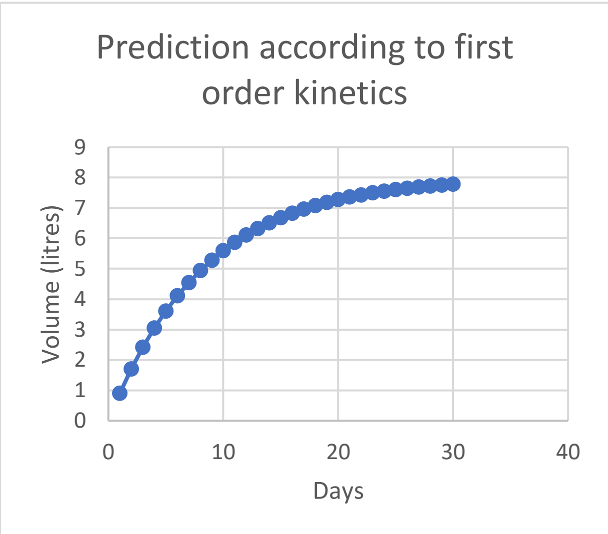
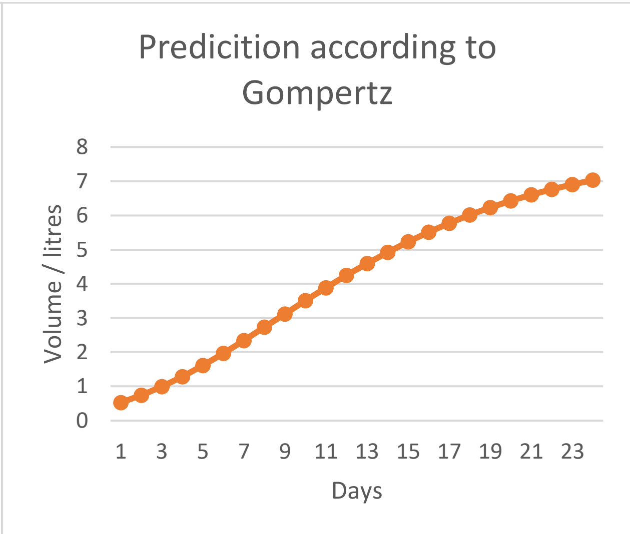


Figure 18: Gompertz biogas yield for food waste



1 https://www.researchgate.net/publication/283761096_Experimental_and_kinetic_study_on_anaerobic_digestion_of_food_waste_The_effect_of_total_solids_and_pH?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6Il9kaXJlY3QiLCJwYWdlIjoicHVibGljYXRpb24ifX0

2 Qamaruz-Zaman, N, Milke M ; 2010, Predicting the performance of a continuous anaerobic digester from batch scale laboratory studies

2.1.1 Method

Experimental setup:

We decided to use water displacement method to measure the volume of biogas being received. The rig was designed to hold a 12 litre bottle to which a tube will be inserted through water so that the gas can accumulate in the bottle and displace the water accordingly. The rig was constructed with 9 1/2 inches by one inch fascia timber board. It consisted of a base and one side fixed with the other side fixed with drop down hinge mechanism. A piece of electrical wire was used to hold the bottle upright fixed with two screws at both ends (figure 17).

Digester

The reactor was initially made with 1.5 liter PET sprite bottle with an intended design volume of 500ml. A hole was drilled in the cap and a superglue applicator nozzle inserted in the cap. The area around the nozzle was fixed with hot glue and a layer of superglue both on the inside and outside. A 8mm tube was connected to the nozzle. However, the reactor leaked under testing and had to be scrapped. A store-bought pressure cooker was used as the final reactor (see plate 1) made up to volume of 2.5 litres as given in the table 1.

Gas collector

A 12 litre used clear plastic water bottle was used for gas collection. The bottle was pre-calibrated with one litre graduation marks by addition of one litre of water and marking it with a permanent marker. This was repeated for 12 litres to crate the graduated container. The bottle was first filled to the brim with water, covered with a plastic film and inverted into a water bath. A round plastic screw with a vertical centre hole from a child toy slide was drilled with four horizontal holes one of which was inserted the 8mm gas tube and the others for water to evacuate the gas collector. The gas collector was carefully mounted on top of this and air entry prevented.

Feedstock: The feedstock consisted of blended rice and potato peel with solids. 40g was weighed out and mixed with100ml. This slurry was mixed with 400 ml of water composed of equal part water and cow dung extract obtained from a nearby farm. The reaction volume was 500ml. However, since the first experiment had a gas leak the experiment was restarted with a pressure cooker. For this second trial it was decided to acclimatize the bacteria with the feedstock first by starting with 1.6% solids, then increased to 3.2% after 6 days and then finally to 8% after 11 days.

Plate 1: Initial and final methodology for reactor and gas outlet

In the initial reactor (left), the area around the nozzle lost pressure as can be seen by gas escaping out of the lid. Inspection revealed that the glue had detached on the inside and cracks had appear in the hot glue. This necessitated a complete review of the small-scale materials, in particular the need for a good pressure vessel and a larger hose to reduce built up pressure and allow more gas flow. The final reactor (right) was a store bought 5 litre pressure cooker. An 8mm clear plastic tubing with a jubilee clip was assembled as below. The reactor volume was made up to 2500ml and 200ml of the original cow dung concentrate was used. The feedstock was 40g of rice that had been blended for 40 seconds. The run was started and within the same day, gas was received in the collection tank which according to literature is carbon dioxide and not methane.

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The full small-scale rig is shown in figure 19. In order to measure progress, one photo was taken every day at around 9 am.

Figure 19: Small scale plant rig and final setup

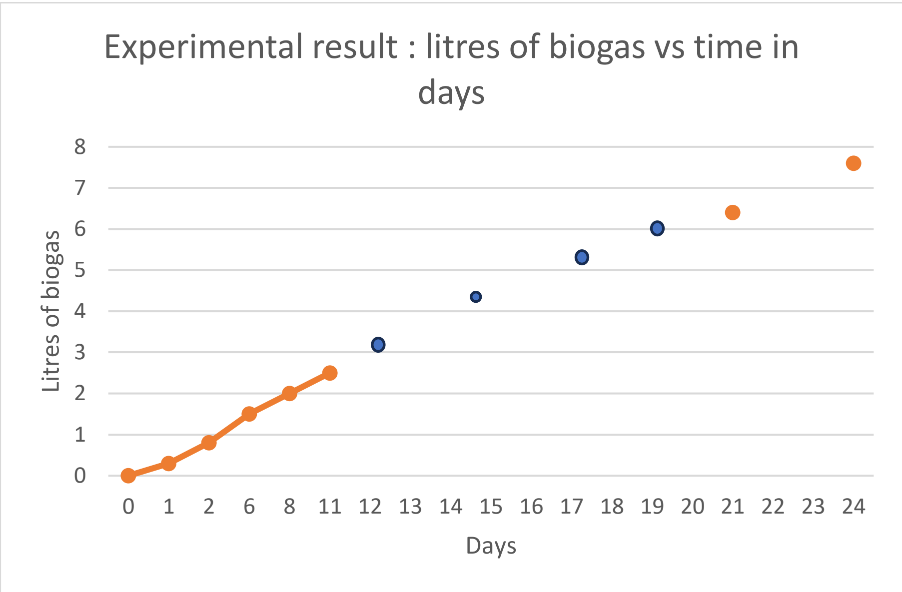
Plate 2: Feedstock preparation and cow dung inoculum

2.1.3 Results

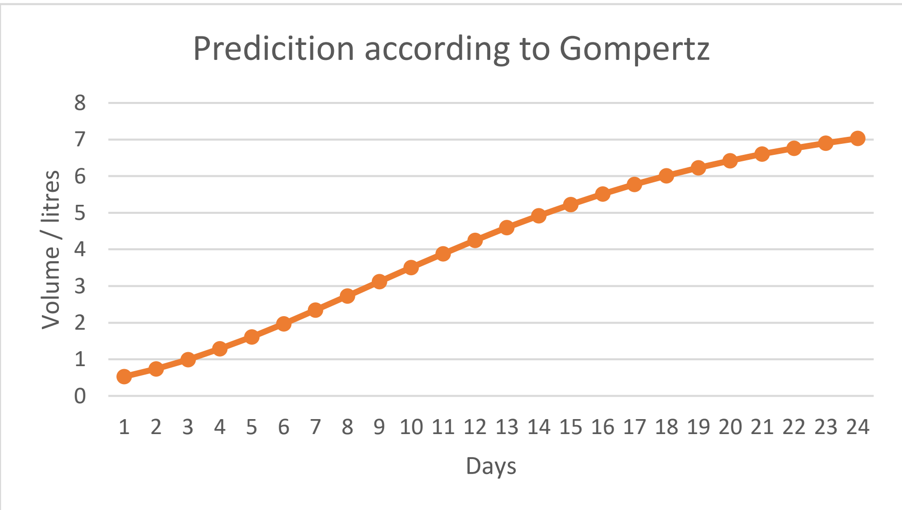
The results of this pre-lab experiment in figure 20 confirmed the theoretical predictions based on Gompertz rather than first order kinetics. It was found that gas production was around 200ml / g (VS). The break in figure 18 was due to a 10 day leave of absence and an extrapolation is made in blue to try and follow this curve.

It is to be noted that after 24 days some errors were introduced as the reactor was opened and additional feedstock introduced. Air was forced into the gas collector so the experiment was stopped.

Figure 20: Results from the batch test



We can do a side-by-side comparison with figure 18 (reproduced again below) to show that indeed the test matches more closely the Gompertz model with yield of 200ml/g for food waste.



This simple test provided a good idea on the biogas potential of food waste, confirming the biogas yield that is applicable to this feedstock. However, it was found after 24 days that biogas production rate had decreased which necessitated opening up the pressure vessel to have a look. Additional feedstock was introduced but there were no significant improvements. Test conducted with a small amount of bicarbonate of soda showed strong effervescence indicating acidity. At same time use was made of a pH meter bought online and it registered a pH of 4.3 (figure 21). This meter was not very accurate and calibration was difficult nonetheless by measuring deionized water (presumed to be at 7) and the digester solution made for a useful comparison and conclusion that it was too acidic

Figure 21: Measuring the pH of the digester after 24 days

We made use of bicarbonate as it was easily accessible however this is not recommended since carbon dioxide arising from this neutralization reaction will now contaminate the biogas generation. Sodium hydroxide is a better choice as it does not produce carbon dioxide. In view of the above, the continuous use of this setup had to be abandoned since it had more or less served its purpose in the kinetic study.

Another reactor was designed for continuous feeding and to be able to learn more about the acidity problem by varying the organic loading rate. Two reactors were built for this next stage described below.

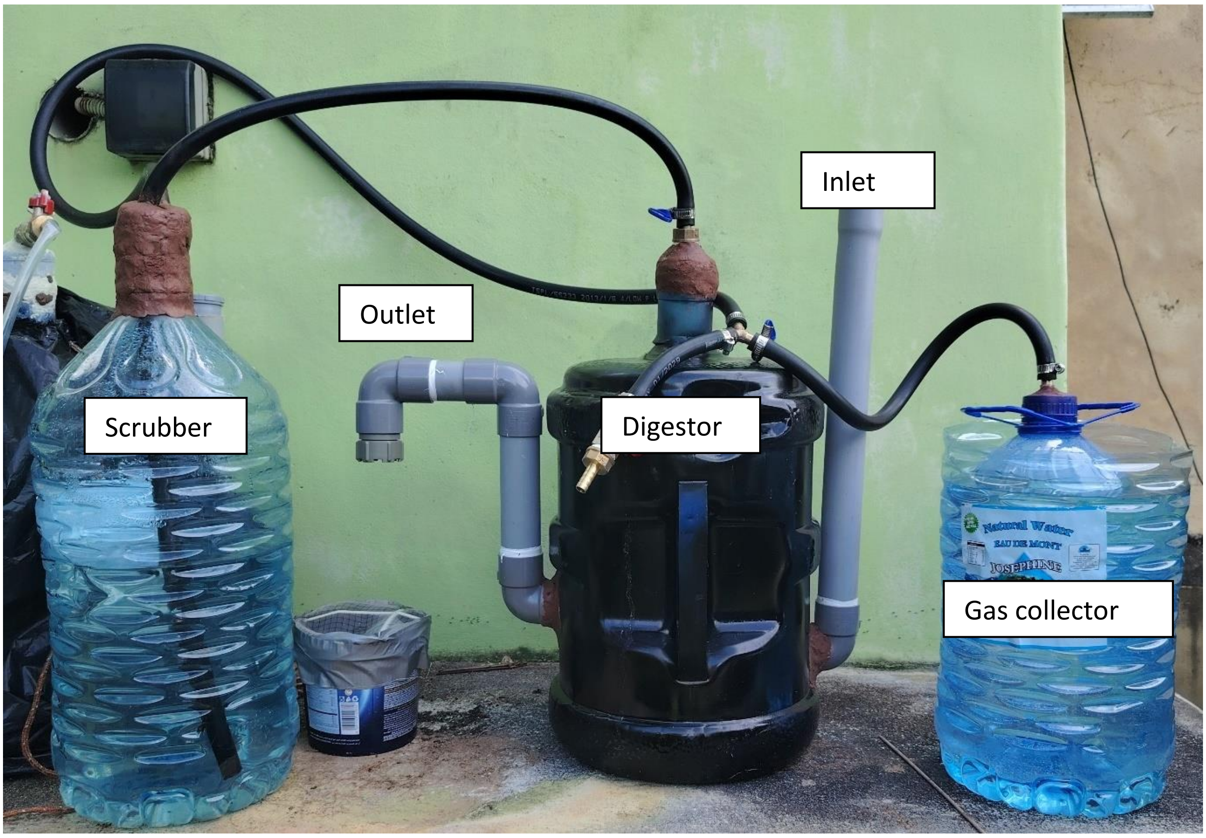
2.2 Operation of a continuous Flow Digester

The second small-scale test involved the design and construction of a 20 liter continuous flow digester. Compared to the pressure vessel, this digester can be fed with feedstock continuously over the course of a week or months to test out design elements and operating conditions.

2.2.1 Design

The setup is shown in figure 22 consisting of a black painted 20 litre PET bottle digester with 40mm PVC pipes and fittings installed for the inlet and outlet. At the top, ½ inch copper fitting was used with gas tubing obtained from the gas station and secured with jubilee clips. The gas is passed through a water scrubber / flame arrester and then onto a gas collector. The gas collector was made with 5 litre waste bottle inside a 12 litre bottle whose top was removed and filled with water. As the gas moves from centre to left in the photo below it is scrubbed and then goes to the gas collector. There is a valve on this line to allow the gas to be tapped off from the system.

Figure 22 : Continuous feed small scale setup



The design parameters are summarized in table 2.

Table 2 : Design parameters for continuous feed digester

Starting material	Amount	Units	Other units
Feedstock solid	40	grams	0.04kg
VS (90%) (estimated)	36	grams	0.036kg
Reactor volume	20,000	ml	0.02m3
Organic loading rate	0.0018	g/ml	1.8 kg/m3

2.2.2 Seeding and startup

The reactor was filled with 12 litres of water to which was added 5 litres of cow dung water slurry in 1:1 ratio. 200g of mixed potatoes and potato peeling was added to the reactor and left to ferment. After few days it was noticed that gas was being collected in the gas collector. This setup allowed the testing of batch feed namely as new feedstock was added an equivalent volume was removed from the outlet. The inlet has to be above the outlet so that hydrostatic pressure is used to push equivalent volume out rather than it backfilling the inlet pipe. This setup worked reasonably well but the following improvement was found wanting;

- A T at the outlet to prevent possible syphoning effect (not addressed)
- The scrubber inlet port was too deep inside the water resulting in a greater pressure to push biogas through (addressed)
- There was too much voidspace above the water in the scrubber. It meant that it was holding on to a large volume of biogas and not sufficient was reaching the gas collector. The scrubber was eventually replaced with a 5litre bottle.
- Long tubes from digester to scrubber and gas collector just introduced more air into the system and required greater amount of gas to push through. These were subsequently reduced in length.
- The testing nozzle was found too big for the setup and the gas tubes could have been smaller in diameter. This meant that testing the gas was difficult. A small nozzle was used to increase gas speed at exit and this worked well.
- A copper ball valve was initially placed on the digester but suspected of leaking and was removed. Inspection showed a black deposit inside due to copper sulfide proving that indeed hydrogen sulfide is produced and attacking the copper fitting. The valve was discontinued and a scrubber was built to remove contaminating gasses.
- The 5 litre gas collector rose a few levels but did never functioned properly. It was felt that there is a gas leak as calculations shows that the gas had enough pressure to push down that volume of water. The 5 litre gas collector was replaced with a 1.5 litre collector (see plate 3).

The 1.5 litre collector filled with gas during the day and was ignited at night to confirm methane since the flame can be difficult to see during day time. The reactors were fed 40g of feedstock daily and one of the two was fed 100g per day. After three weeks it was noticed that gas production was decreasing in both reactors with complete cessation in the latter. Testing with a pH meter showed similar acidity problem (pH 4.6).

This time, we made use of sodium hydroxide from drain cleaner (figure 23) . A 1 Molar solution was made and 500ml poured in. After noticing that the pH did not change much, a 0.5 Molar solution was prepared with sodium hydroxide flakes and 1000ml poured in. Safety precaution (safety glasses) was adopted when handling the caustic soda. Additionally, 750ml of clean water was added to dilute the solution. This crude approach seems to work as gas production resumed during the night however it was later found to be non combustible. We clearly missed an important point of weak acid strong base neutralization in that a buffer solution is formed. It takes time for the change to happen to the pH so we used far too much base (see annex 1 for calculated amount to use) and the process was killed.

Figure 23 : PH adjustment with caustic soda from drain cleaner

In the high loading digester, it was noticed that the pH had turned highly basic since neutralization point had been surpassed. In retrospect, we should have calculated the concentration of H^+ from the pH value and determined the exact amount of base we needed to add for neutralization. Since we did not do this and instead relied upon just adding and checking pH we ended up at the other end of the scale. As a result, all bacteria was killed. A day later the vessel started leaking possibly due to base attacking the plastic and therefore one of the two digesters was abandoned. This left one reactor still working to continue testing the pH and gas production rate. This reactor was modified to allow for mechanical mixing by a copper pipe attached to plastic bulge from a big plastic lollipop that had been cut to act as propellers. This was found to be very effective.

Plate 3 shows the successful use of this digester generating methane gas alongside the gas collector used and scrubber made of steel wool.

PLATE 3: 1.5-liter gas collector, gas testing, damage to copper pipe and H2S scrubber

2.3 Summary of results

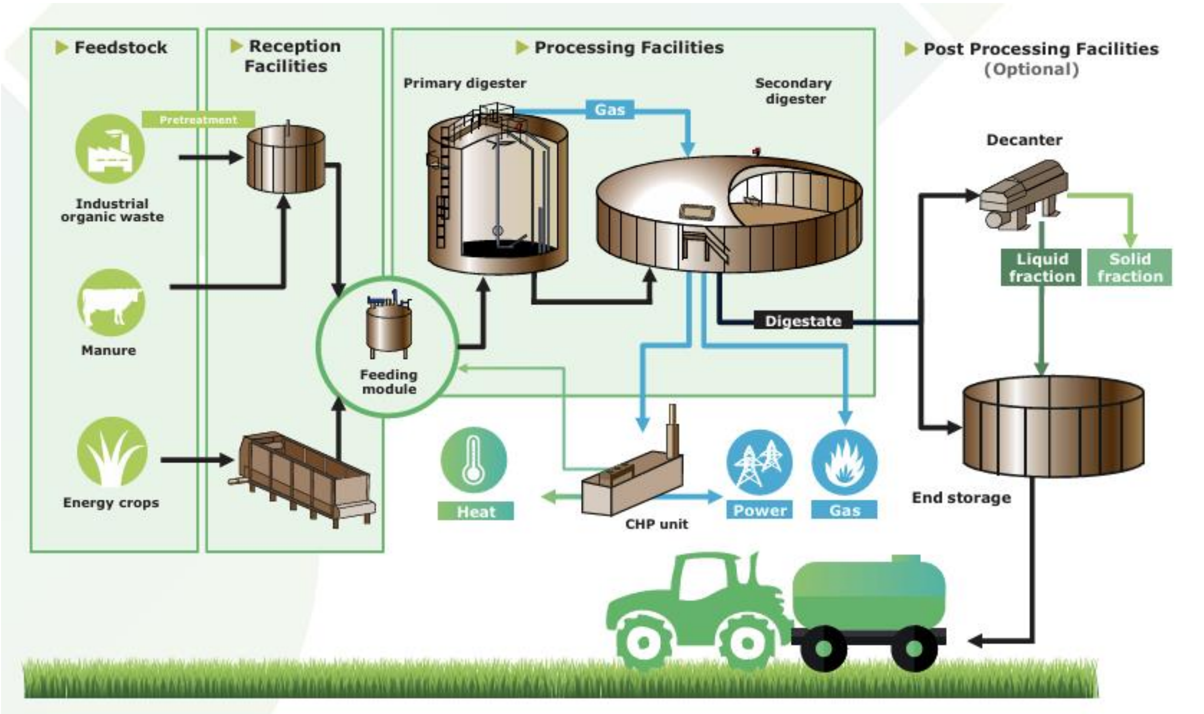
The two small-scale experiments provided several insights

1. **Macerated feedstock:** Feedstock that was blended was more manageable for feeding into the apparatus, and better to increase rate of reaction in terms of surface area. Some sort of mechanical shredding is recommended for the full scale plant.
2. **Temperature:** Production of gas was greatest at midday being the hottest time of the day. Whenever it was cloudy or raining very little gas formation was noticed. It is recommended that digester be kept in a very sunny area or incorporate a temperature regulating device.
3. **Darkened reactor:** Darkening the reactor seems to have more impact during the initial test. This could mean that activity might be impeded by light. As such painting the reactor black improved activity.
4. **Mixing:** Gas production increased when the digestor was mixed.
5. **pH:** The monitoring of pH is important and was difficult without good instrumentation. Larger plant need to have pH sensor and dosing mechanism.
6. **Gas volume:** Gas production was below theoretical prediction for both models. It may be because of poor mixing and lack of temperature control.
7. **Safety:** Upon testing methane produced in the 12 litre container in the kinetic trial, the gas exploded showing high contamination of air. This reminded us of the safety aspect that is required. In particular no smoking sign, flushing reactor and collector of air, provision for gas monitoring device.
8. **Gas pressure:** For the continuous digester the gas was successfully ignited without any problem. However there, the pressure was low. It was decided to use a small nozzle which gave better result. This shows the need to calculate pipe diameter based on desired pressure.
9. **Material choice:** The copper fitting for the continuous digester had a deposit of copper sulfide from reacting with Hydrogen sulfide in the biogas. It is suggesting the need to use plastic fittings as far as practicable and available on the market. Gas leaks were common. Therefore materials (adhesive) had to be continually researched that can provide perfect seal. Bisphenol A based epoxy resin was used to seal the joint and this was applied only to outside since it was not possible to reach inside the small digester. Later, automotive engine gasket sealer was used to coat the hardened epoxy for better seal.
10. **Design:** It was seen that continuous batch feed design work well and displaces in the outlet the same volume of liquid that entered the inlet. Nonetheless as pressure builds inside the vessel it pushed out the liquid from both inlet and outlet. This necessitated using ball valves for inlet and outlet to open only when feeding. The inlet has to be always higher than outlet.
11. **Scrubber:** A Hydrogen sulfide scrubber was constructed out of steel wool and tested. After a month the copper fitting in front was examined and no damage was seen suggesting that iron wool does clean up hydrogen sulfide.

3 Technical Feasibility of scaling AD in Seychelles

This chapter now considers the implication of scaling up AD in Seychelles to a large centralized facility. Such facility is expected to have a reception facility, primary and secondary digesters for the waste, storage tank for digestate and possibly post digestate processing. Additionally, it will have areas to scrub gas and machinery for power generation, heat or combined heat and power. This is shown in figure 24 below.

Figure 24 : Steps at an anaerobic digestion facility



Source: http://www.cre.ie/web/wp-content/uploads/2018/03/Guidelines-for-Anaerobic-Digestion-in-Ireland_Final.pdf

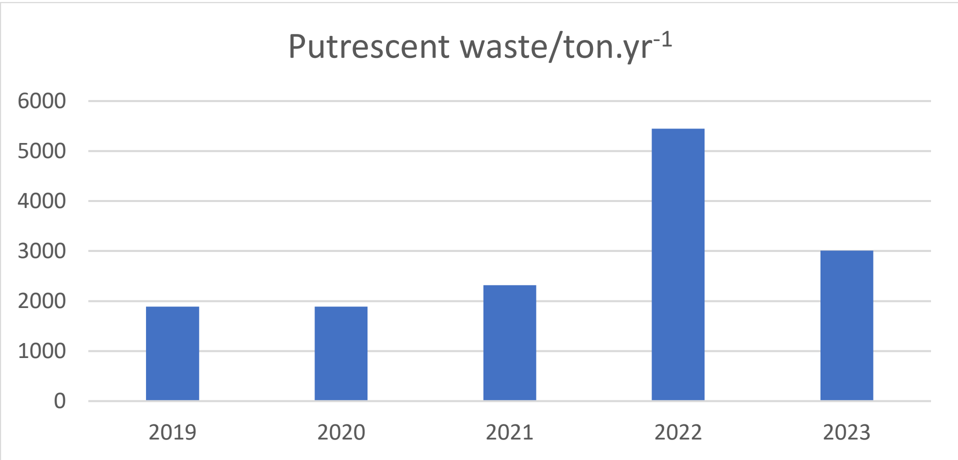
Large AD plants function under thermophilic conditions with temperature around 55 degrees and continuously stirred as this us much more efficient and leads to faster degradation. It also allows for high organic loading compared to mesophilic conditions. The result is a lower hydraulic retention time that translates to smaller tank volume. All this leads to cheaper build cost.

From research conducted the organic loading rate for unstirred reactor is between 0.5 – 2 kg/m^3 while for thermophilic continuously stirred reactor it can be up to 7.5kg/m^3.

3.1 Potential feedstock (municipal vs commercial waste)

A centralized facility will require a constant supply of organic waste, so the organic waste generation rate in Seychelles for such a plant need to be established in order to calculate a flow rate. Putrescent wastes (class 3B) are organic waste that are rapidly degraded and smelly coming from industry e.g. abattoir and IOT and good feedstock for AD. Data from the Landscape & Waste Management Agency (LWMA) for this waste entry into the Providence landfill for the period 2019 to 2023 is shown in figure 25.

Figure 25: Biowaste entry into Providence Landfill



We can conclude that over the last three years, the average organic waste generation is 3,600 tons per year. If this is blended at 40% slurry then the total tonnage per year will be 5040m^3 or just under 14m^3 per day. A plant with design margin of 20% can be designed for 17m^3/day (17 tons/day) and perhaps for our purpose we will use an initial flow rate of **20m^3/day** (7300 tons/year).

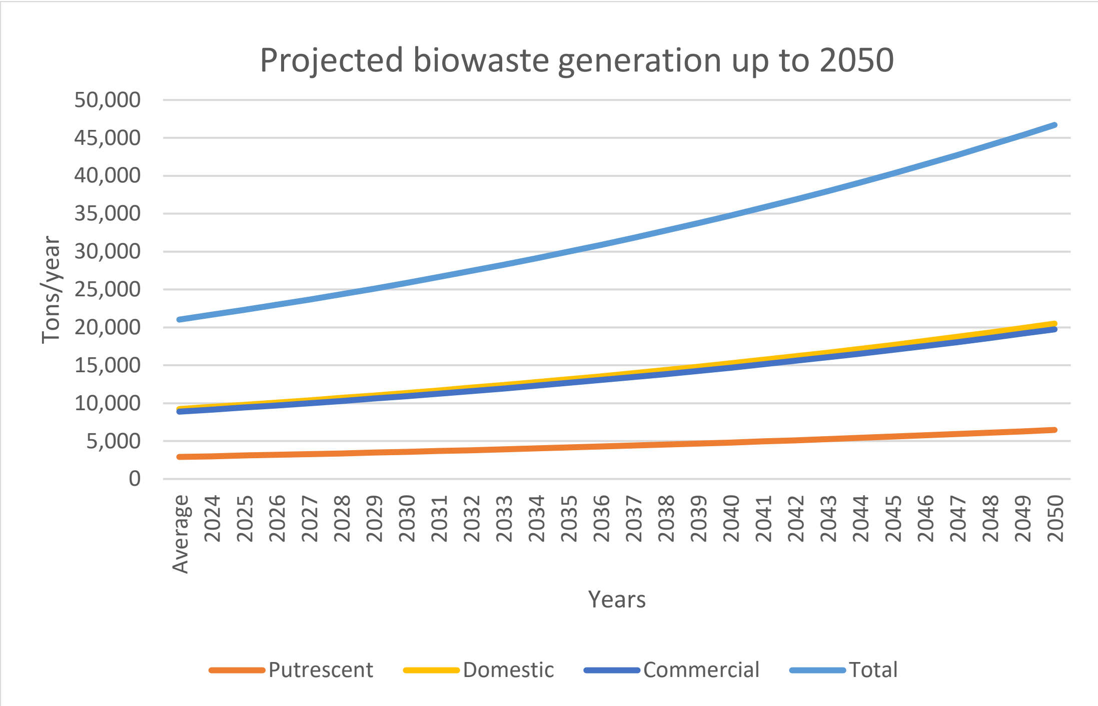
We must however take into account the fact that plants are built for its intended lifetime and also the fact that organic waste are present in two other waste streams coming into Providence landfill, namely mix commercial waste (class 2) and municipal waste (class 1). However the biowaste fraction in these streams are unknown and characterization study done previously (ETH Zurich) places it at 31%. Under the TWENex, a characterization study will be done to update these figures. Nonetheless, taking maximum of 40% for both streams one can estimate the amount of total biowaste going to landfill for the period 2019 to 2023. This is shown in the table below.

Table 3: Biowaste generation in Seychelles from 2019 to 2023

	Fraction	2019	2020	2021	2022	2023	Average
Putrescent	100%	1,888.32	1,889.89	2,320.43	5,450.44	3,012.08	**2,912**
Commercial	40%	11,463.94	8,152.40	7,087.05	8,638.88	9,094.49	**8,887**
Domestic	40%	9,157.82	9,258.86	8,424.96	9,424.05	9,870.38	**9,227**
Total		**22,510.07**	**19,301.14**	**17,832.44**	**23,513.37**	**21,976.94**	**21,027**

We conclude that a total of **21,027** tons of biowaste are available yearly for anaerobic digestion. Taking lifetime of 15 years and 3% annual growth in waste, we can estimate that the amount in 2041 will be **35,797** tons.year^{-1}. Assuming wet AD with 1:1 mixing with water, the input wastewater volume will be approximately **196 m^3/day**. Figure 26 below shows the biowaste projection up to 2050.

Figure 26: Projected biowaste production in Seychelles up to 2050



3.3 Design

The design will be a large-scale reactor operating under thermophilic range (55C) and be continuously stirred. For continuously stirred system the most optimum[3] organic loading rate (OLR) is 3.6 kgVS/m^3, however it may be operated higher and for this design we will use 7.5 kgVS/m^3. Table 4 summarizes the design parameters for such a plant.

Table 4: Design specification for large AD plant

PARAMETER	VALUES	UNITS
TONNAGE	35797	Tons/year
FLOW (150 M3/DAY)	196	m^{3}d^{-1}
HRT	60	days
TS	98,074	Kg. day^{-1}
VS	88,267	kg. day^{-1}
ORGANIC LOADING RATE (15,300/4250)	7.5	kg.day^{-1}m^{-3}
DIGESTOR VOLUME (90%)	11,769	m^3
DESIGNED GAS COLLECTOR VOLUME	1,308	m^3
TOTAL TANK VOLUME	13,077	m^3
TEMPERATURE	55	degrees
GAS YIELD CONSTANT	0.10	m^3.kg^{-1} VS
TOTAL GAS YIELD	8,827	m^{3}d^{-1}

The facility will require 2 vertically cylindrical tank with a cone top ($V = 5{,}884$ m^3, $\emptyset = 34\text{m}$, $H = 8.6\text{m}$) and gas storage volume of 654 m^{3}each. This digester will allow a hydraulic retention time of 30 days each and at its peak will generate 3,221,730 m^3 of biogas yearly.

3.4 Health & Safety aspects

A large plant would have sensors to detect leaks within pipes, gas metering system to record the amount of gas being produced and inline flame arresters to prevent explosion. Large AD plant need to be protected from lightning as well and should have pressure release valve to prevent explosion of the digester due to blocked gas pipes.

The gas should be scrubbed of contaminants and dehydrated through silica gel or by using cold temperatures. This will prevent condensation problems which can lead to blockages.

The facility and various tanks should be adequately labelled and bear no smoking signs.

[3] L. Megido, L. Negral, Y. Fernández-Nava, B. Suárez-Peña, P. Ormaechea, P. Díaz-Caneja, L. Castrillón, E. Marañón, Impact of organic loading rate and reactor design on thermophilic anaerobic digestion of mixed supermarket waste, Waste Management, Volume 123,

As these plants need to correct the pH, it will have chemical dosing and storage of caustic chemicals. These should be adequately labelled and there should have a wash station in case of accidents.

3.2 Biowaste collection program

If the country is to embark on a centralized AD plant, then it is conceivable that a biowaste collection program will need to be rolled out to ensure constant supply of feedstock for digestion. For this it is recommended that a separate organic waste bin be placed at the communal bin site for collection every day while the other bins for non-organic may be collected at reduced frequency, such as twice or thrice a week depending on location. This has been talked about for many years in Seychelles and trialed but not successfully implemented.

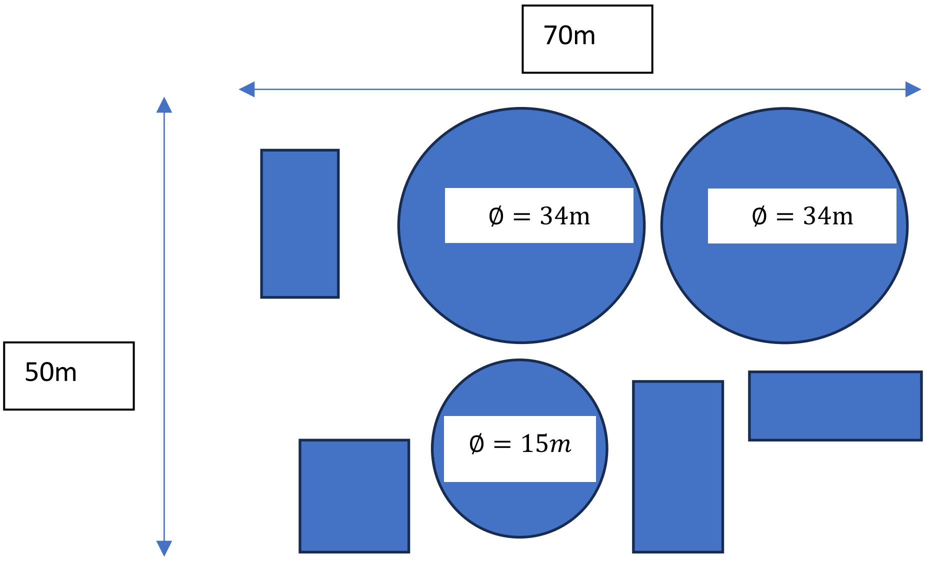
Under the integrated waste management programme in the waste master plan 1996-2006 biowaste was to be collected separately for composting. A brown bin was placed at the communal bins for organic waste which was to be collected daily with reduced frequency on the green bins. To implement the scheme a materials recycling facility (MRF) was constructed by the waste contractor STAR Seychelles to produce two grades of compost, a high-end compost from green waste and a low-grade compost from household organic waste.

The MRF was designed to sort out municipal waste both mechanically and manually comprising of a floor for people to undertake manual sorting of waste. The recyclables and inert materials would be placed in different bins under the facility. Trials conducted was not encouraging with the contractor refusing to undertake the sorting on account of smell, flies and poor condition for workers. The contractor focused on composting of green waste and sewage sludge instead producing the high-quality compost. As the biowaste collection program was abandoned and the contractor was found putting both bins in the same truck for disposal, residents were discouraged to separate out their biowaste.

It is conceivable that a biowaste collection program for municipal waste is still practicable in Seychelles however it may not do well for AD. An industrial source of biowaste may prove to be more effective primarily because of non-variable feedstock which will less likely shock bacteria. This can be waste coming from IOT or other fish processing area, the PUC, Seychelles Breweries and food waste that are not being sent to livestock. Additionally, the facility could take rejected condemned goods such as fruits and vegetables.

3.5 Space requirements / location

An AD plant will have a reception facility, waste shredder, equalization tank, treatment tanks, digestate withholding tank, biogas storage tank. Taking into account 2 digestor tanks, scrubber units and power production, one large digestate tanks and a site office, the site footprint is estimated at 3500m^2. A possible schematic for this is shown below.



As an example, the site at IOT is treating 1000 m^3 day which is 50 times this flow and has a footprint of 5,500 m^2. However, this company is processing industrial waste and do not have some of the steps associated with solid waste processing area. The google earth image below is from the Providence landfill facility and shows an area equivalent to 5,212m^2 that can comfortably accommodate a biogas plant with all amenities (estimated at 3500 m^2). The maximum height of infrastructure will be 8.6 meters, well below the height of the landfill. This plant may also be able to tap into the landfill gas being produced at the landfill I and II to generate additional energy. However, it is important to realize that such facility will not replace a landfill. There will continually be non-organic waste that cannot be recycled and which will require disposal.

Another advantage of siting such construction near the landfill is that the digestate if still active can be circulated to Providence II where it can undergo additional treatment and gas captured for energy recovery. The landfill can therefore be used as a buffer area for the digestate in case of emergency (see 3.7 on management of digestate).

3.6 Use of gas

3.6.1 Cooking

The most common use of small to medium biogas plant is as a fuel for cooking. Biogas have heating value equivalent to 17MJ/kg which is less than that of LPG (45.7MJ/Kg). This is because biogas have in addition to methane, carbon dioxide and other gasses in trace amounts that are not combustible. Because of this, stoves using biogas must be configured to allow mixing of a greater amount of air with the gas for combustion.

Also, since biogas is of lower pressure that LPG, the delivering nozzle that converts high pressure to low pressure is not needed. This means that normal stoves cannot be used with biogas and special biogas stove need to be procured or existing ones modified. In figure 27 we can see a high-pressure nozzle for LPG stove and to the right being modified to run on biogas.

Figure 27: Modification of gas nozzle size for biogas (left before and right after)

3.6.2 Heating

Biogas can be used to heat water for various uses including domestic households and industrial uses. There are biogas water heaters on the market for domestic use that connect to the biogas line and a water line. Whenever hot water is required, the unit is switched on and the gas is ignited automatically to heat up the water. The water temperature is automatically kept constant for bathing use by mixing with incoming cold water. A typical biogas water heater is shown in figure 28. Such systems are good for households and may be considered in decentralized AD plants. For large scale AD plant, the heating will be trough a biogas boiler that generates steam for industrial application.

Figure 28: Water heater using biogas

3.6.3 Transport fuel as compressed natural gas (CNG)

Biogas may be compressed and stored into gas cylinders. However, the biogas inside the tank is in gaseous form and not liquid. This means that the volume occupied by biogas is significantly less than for liquified Petroleum gas (LPG). Similar sized small tank of LNG will outlast that of CNG by a factor of 600. It is ideal for low application use but larger tanks are required to last as long as a small LNG tank. This has not stopped the use of CNG to power vehicles as seen in figure 29 from Philippines. See also case study from HEMAB Sweden (page 50)

Figure 29: CNG in cylinder being changed in the Philippines

3.6.4 Liquified methane (Bio-LNG)

Methane can be compressed to a liquid at 650 PSI (@25C) or at a temperature of-160C. This makes the process of making and using liquified methane problematic and out of the range of developing countries. Liquid methane from Biogas is known as Bio-LNG (figure 30) and as expected it is made by liquifying the methane component of biogas. The process starts with generation of Renewable Natural Gas (RNG) which is biogas from which the other gasses such as carbon dioxide has been stripped. The RNG is then cooled at -160 C to generate Bio-LNG. Special cryogenic apparatus is used to hold the cold liquid for use as energy. The RNG making process can also produce liquified CO2 which can be sold to industry.

Figure 30 : Liquid biogas methane (also known as Bio LNG)

The Wipptal (BiWi) plant in Austria is an example of a facility that creates Bio-LNG and liquified CO2 for the transportation sector and industry. Table 5 shows the components and properties of biogas compared to natural gas and liquified Petroleum Gas (LPG).

Table 5: Difference in properties of LPG, natural gas and biogas.

Propriedade	GLP	Natural gas	Biogas
Composition	C_3H_8-30% C_4H_{10}-70%	CH_4-85% C_2H_6-7% C_3H_8-2% N_2-1% CO_2-5%	CH_4-57% CO_2-41% CO-0,18% H_2-0,18% Traces of other gases
Heating value less than 1 atm. and 15ºC (MJ / kg)	45,7	50	17
Density at 1 atm. and 15 °C	2,26	0,79	1,2
Flame speed (cm/s)	44	34	25
Stoichiometric A / F (kg in air / kg in fuel)	15,5	17,3	5,8
Lower flammability limit (% vol. In air)	2,15	5	7,5
Upper flammability limit (% vol. In air)	9,6	15	14
Octane number			
Researches	103-106	120	130
Engine	90-97	120	-
Auto-ignition temperature (ºC)	406-450	540	650

Source: Yadav et al, (2013)

Adapted from Bezerra[15]

The main gas in LPG is butane which can be compressed at 32psi at 25 C. It is the reason why butane is extensively used in the domestic sector as a liquified fuel source.

3.6.5 Electricity production

An important use of biogas is in the production of electricity. Here the biogas is essentially the fuel source and is fed directly into the generator chamber and ignited. There exist small to large sized generators running on biogas. As can be expected the gas need to be scrubbed and dried to feed into the generator. The example in figure 31 is a small 15KWh biogas generator from China.

The amount of electrical energy recovered is generally less than what is theoretically possible due to loss of energy as heat. The efficiency is around 40%. However, heat can also be harnessed and used in the process. Table 1 below shows the useable energy available for electricity generation compared to heating directly for use in boiler. We can see that direct use of biogas for heating is much more efficient that using it to generate electricity. However, both processes can be combined in a Combined Heat and Power (CHP) unit to maximize the extraction of energy.

Figure 31: Small generator utilizing biogas

Table 6: Efficiency of electricity production vs heating

	M3 biogas	M3 methane	Energy conversion	Usable energy kwh
Boiler	1	0.53	80%	4.7
Electricity			40%	2.35

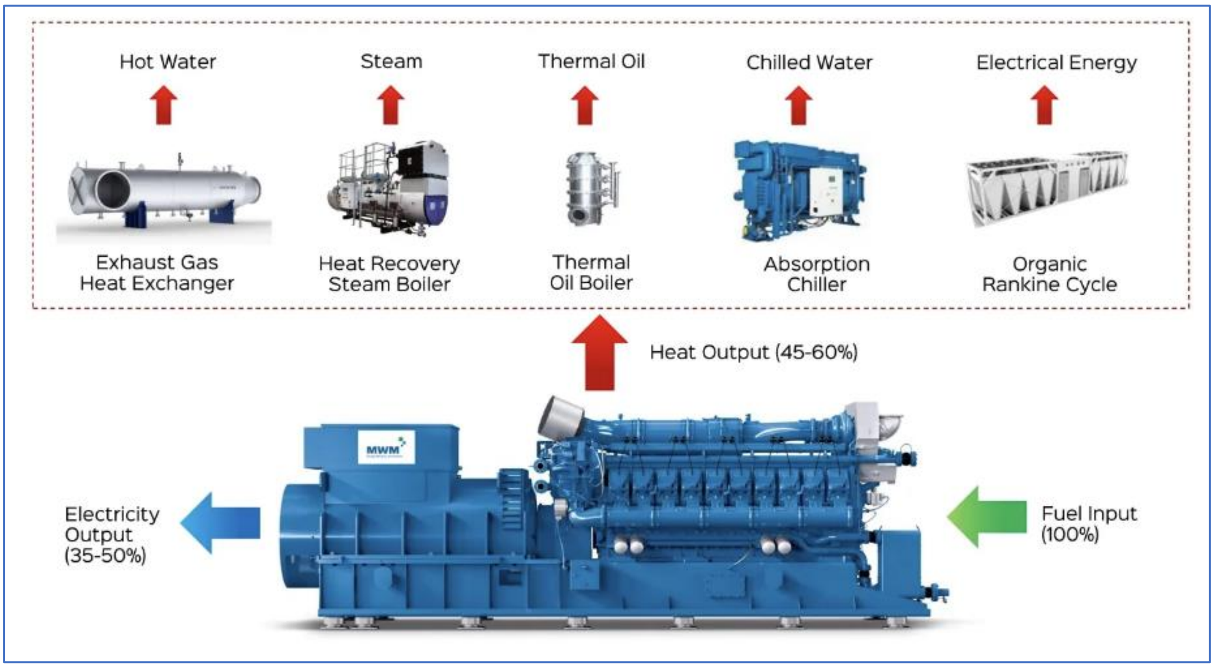
Therefore 8,827m^3 of biogas will generate 20,742 Kwh per day which is around 7.5GWh per year.

3.6.6 Combined Heat and Power (CHP)

As stated above, a Combined Heat and Power (CHP) plant produces electricity from the combustion of biogas in its chambers and at same time recovers the heat produced by using the circulating cooling water for other application. CHP provide the most efficient use of energy from biogas as energy conversion to electricity is not very efficient.

These plants range from 400kw to 800KW for electricity production[4]. The heat can be used to heat boilers, or provide cooling through absorption chiller[5]. (figure 32).

Figure 32: Example of a CHP plant with different uses for the heat generated



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[4]Example at [CES20022 Update Produktbro_TCG 3016_210x297mm_EN_3_0_RZ_sm.indd]

[5][Combined Heat and Power (CHP) | Cogeneration | The Ultimate Guide]

3.7 Management of digestate

The end product of digestion is a nutrient rich liquid known as the digestate. The digestate cannot be discharged into watercourse and requires additional treatment. Below are some common application and post treatment of the digestate.

3.7.1 Farm application

Farm application is the simplest and most cost-effective use of digestate. This is because the digestate can be considered a liquid manure, high in nutrients such as nitrates and phosphates both of which are limiting in soil. Therefore, application of diluted digestate has potential to fertilize the soil and cut back on the use of fertilizer. In a centralized facility the digestate can be diluted and stored in a tank for selling to farmers as liquid manure. There are a number of big farms located at Au Cap and Anse Royale at a distance of 9 -12 km from Providence which can make use of this product. Since the farmers are located along the coast, it will be reasonably easy and cheap for vacuum trucks to transport liquid digestate from source of production to final use.

3.7.2 Composting

Large scale composting requires watering to continue the natural decomposition of organic matter. The addition of wastewater to composting has been extensively studied and found to be useful. Since the digestate has been biologically treated, it can be applied to compost to enrich it further. However, in Seychelles centralized composting is no longer being carried out. This option does not fair very well for the current waste management infrastructure. However, the AD plant can add a composting station especially for digestate as is the case in Hengelo, The Netherlands (figure 33).

Figure 33: Co-composting and AD plant in Netherlands

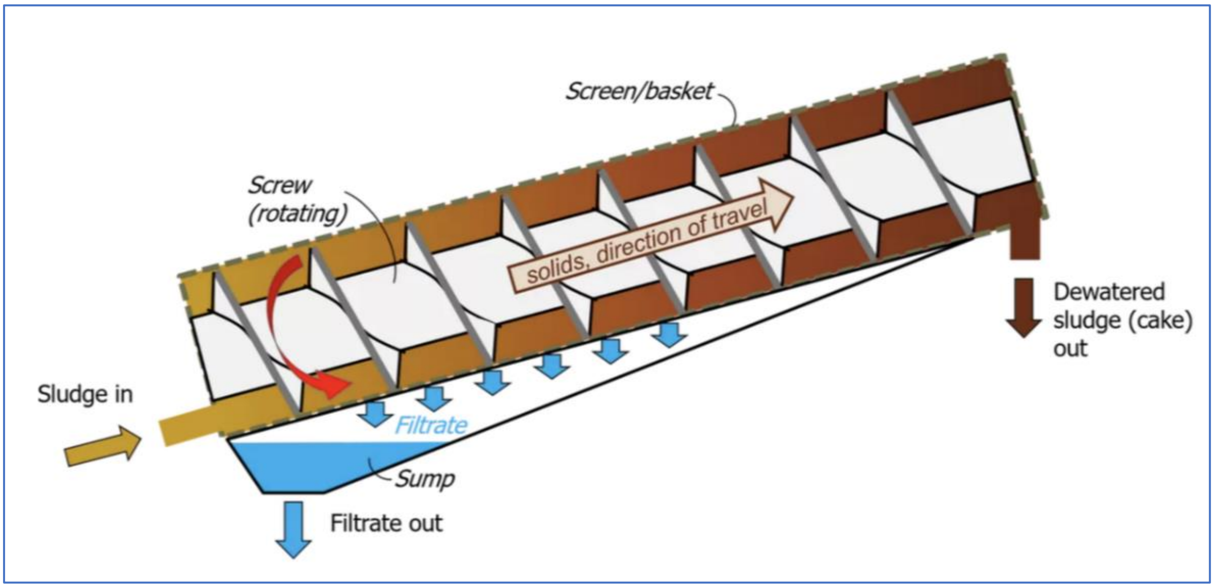
3.7.3 Thickening, conditioning & dewatering

The digestate can be **thickened** by gravity sedimentation or dissolved air flotation (DAF) to obtain **a sludge**, defined with dry solid content (DSC) of around 3%. The water can be sent to treatment plant while the sludge may be sent for conditioning and dewatering. Conditioning involves method to better the water repulsion of sludge before dewatering. The best results are when an inorganic salt and a polyelectrolyte are used together.

Most frequently a combination of ferric chloride, aluminium oxides, and lime is applied as an inorganic salt. Sludge contains three types of water, namely intracellular, free water and capillary water. Free water is easily removed by gravity filtration while the others require more work.

Rotary press: The most common dewatering method is a screw press (figure 34) that mechanically forces the water out, leaving behind a sludge cake that is anywhere between 3% to 20% DSC. The press is inclined at 20 degrees and sludge moves up the equipment by an Archimedean screw rotating at around 5 revolution per minute. There are tiny perforations (0.5mm) in the cylinder where water can escape and the solids trapped behind. The filtrate flows down and collect at the sump. The sludge can then be disposed either to landfill or use in composting. The filtrate from the press do not meet discharge consent and will require additional treatment.

Figure 34: Example of a sludge screw press



Belt filter press: A belt filter press (BFP) consists of two belts that combine drainage and mechanical pressure sequentially by pressing the sludge between the two revolving permeable belts to squeeze out the water from the sludge. This produces a cake (the dewatered product) having a dry solids (DS) content of around 30%.

The sludge is first passed along a gravity drainage section of one of the porous belt and then subjected to pressure as it is passed between two recirculating belts, forming a wedge zone at the inlet, which travel over a roller. The squeezing action from the two belts releases more water.

Many belt filter press contain a second pressure zone (Figure 35[6]) comprising a series of rollers through which the two belts pass with the sludge solids retained between them. The rollers in this high pressure zone apply tensioning (i.e. stretching) to the belts, exerting both shearing and compressive forces on the sludge which further release more water.

Some BFP technologies are based on a three-belt system, where the gravity belt is independent of the two pressurising belts. This allows the recirculation rate for the thickening operation to be separately adjusted from the dewatering operation. The belts are cleaned periodically with water spray to limit the plugging of the filter belt pores. The waste wash water is combined with the filtrate.

Figure 35 : Design of a belt filter press

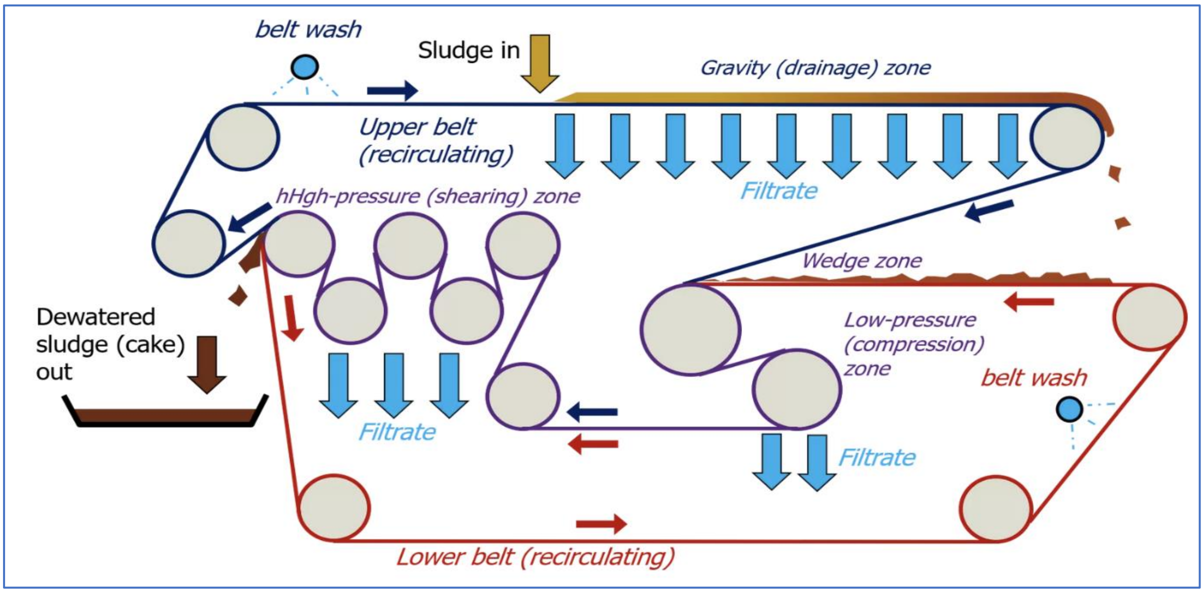


Figure below shows a working model with the sludge cake coming out between the two belts at the end of the process.

[6] *(www.sludgeprocessing.com/sludge-dewatering/belt-filter-press)*

Adapted from www.sludgeprocessing.com/sludge-dewatering/belt-filter-press

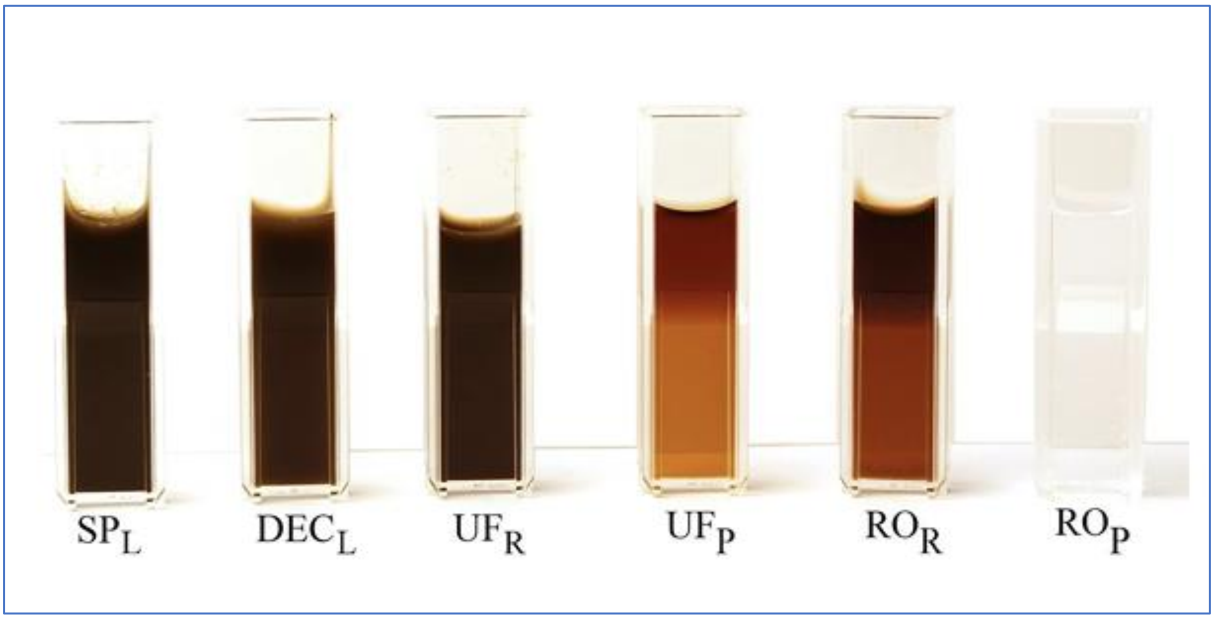
3.7.4 Membrane filtration / Reverse osmosis

Membrane filtration uses fine filters and mechanical pressure to push water out of the wastewater resulting in a concentrated sludge and clean water. The clean water can be discharged to the ocean while the sludge can be sent for composting or disposed at the landfill. The main disadvantage is that it is energy intensive and leads to soiling of the membranes that will require replacement but the process generates clean water that can be reused or discharged directly in the environment. Membrane filtration including ultrafiltration and reverse osmosis are polishing steps after more basic gravity treatment and filtration has been carried out. Ultrafiltration use 50nm pore size and the permeate can be passed through reverse osmosis plant. The RO retentate (see figure 36) can be recirculated in the plant or used as liquid fertilizer.

Figure 36: Ultrafiltration (left) and RO plant (right): adapted form [17]

Figure 37 shows the resulting liquid following screw press (SP_L) Decanter centrifuge (DEC_L), ultrafiltration permeate(UF_P) Reverse Osmosis permeate (RO_P). Reverse Osmosis retentate (RO_R).

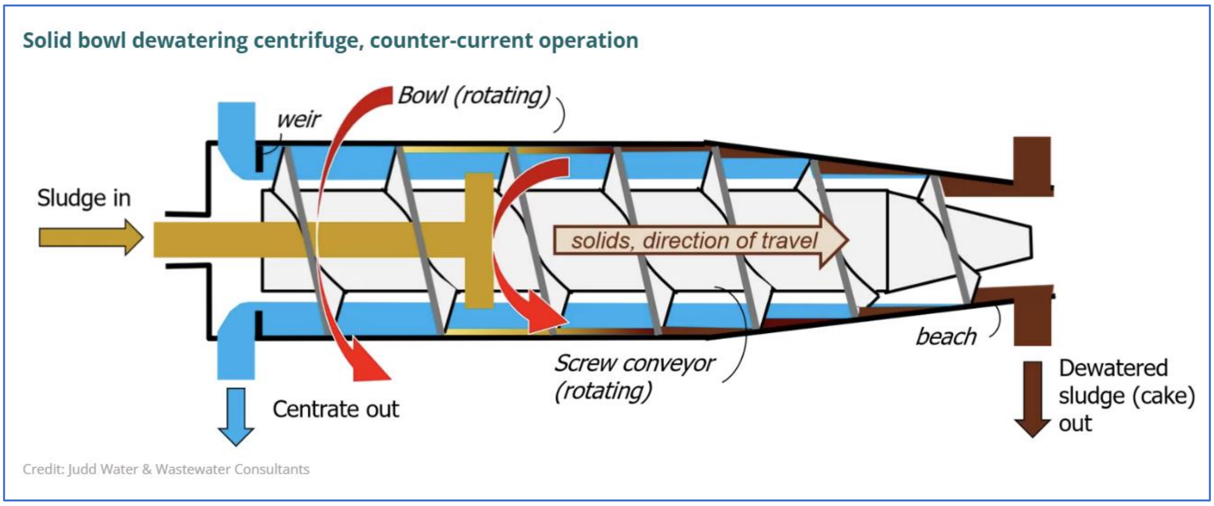
Figure 37: Processing of sludge by filtration and reverse osmosis



3.7.5 Centrifuge

Sludge can be dewatered by centrifuge where a spinning drum pushes the solids towards one end and water is removed from the other end. This is shown in figure 37+8. This system does have some limitations, including **noise** issues, high wastewater treatment energy consumption and the need for a standby unit. It is why other treatment methods are preferred.

Figure 38 : Design of sludge centrifuge



3.7.7 Sonification

Sonification is an emerging and very effective mechanical pretreatment method to enhance the biodegradability of the sludge, and it would be very useful to all wastewater treatment plants in treating and disposing sludge. Ultrasonication enhances the sludge digestibility by disrupting the physical, chemical and biological properties of the sludge. The degree of disintegration depends on the sonication parameters and also on sludge characteristics, therefore the evaluation of the optimum parameters varies with the type of sonicater and sludge to be treated. It can be used before anaerobic digestion to significantly enhance the formation of gas and quality of resulting sludge.

Guangming et al [18] tested both sonication and sonication-chemical co-conditioning with final water content of dry sludge used to represent the sludge dewaterability. Their results showed that sonication significantly changed the sludge dewaterability and the changes were strongly influenced by the ultrasonic power density and time. The best sonication for sludge conditioning, alone or together with chemicals, was 7 s and 0.8 W/ml. The optimal energy dose was 960 kJ/kgDS while energy input higher than 1200 kJ/kgDS deteriorated the sludge dewatering. Sonication alone only reduced the sludge specific resistance to filtration (SRF) by 40% and the final water content to 90%; thus, chemical conditioning was necessary. Combination of FeCl3 and polyacrylamide (PAM) was very effective for sludge conditioning and the optimal PAM/FeCl3 was 0.01.

When chemicals were used, sonication effectively reduced the necessary chemical dose by 40-50% but showed little improvement in resistance to filtation. The best sludge conditioning parameters they found were: sonication for 7 s at 0.8 W/ml, 1.5 g/L FeCl3, and 15 mg/L PAM. A sonicating machine is shown in figure 39.

Figure 39: 48KW powerful ultrasonic processor for sludge disintegration

www.hielscher.com

3.7.6 Thermal methods (Sludge Drying)

Rotary drum dryer

Rotary drum dryers use hot air to gently dry the material as it cascades through the dryer. The hot air is often generated by a direct-fired gas burner that can use natural gas, bio-gas, or other fuels. The inclined dryer slowly rotates moving sludge towards the discharge end of the dryer. Drying happens because of internal lifting flights of sludge that result in sludge tumbling through the warm air stream.

Rotary drum dryers can dry sludge to a Dry Solid Content (DSC) of 90–95%. Drying efficiency can be improved by increasing the internal temperature and the time the sludge spends in the dryer. Some rotary drum dryers have an agitation mechanism that helps improve drying efficiency by repeatedly crushing and dispersing the material. The working principles are shown in figure 40.

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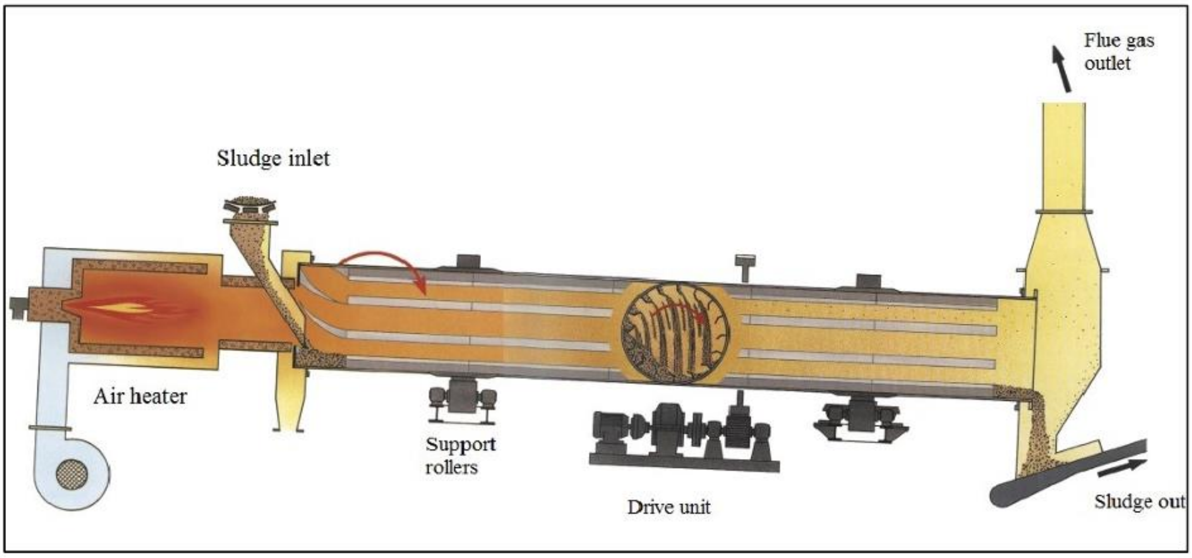
Figure 40: Rotary drum dryer

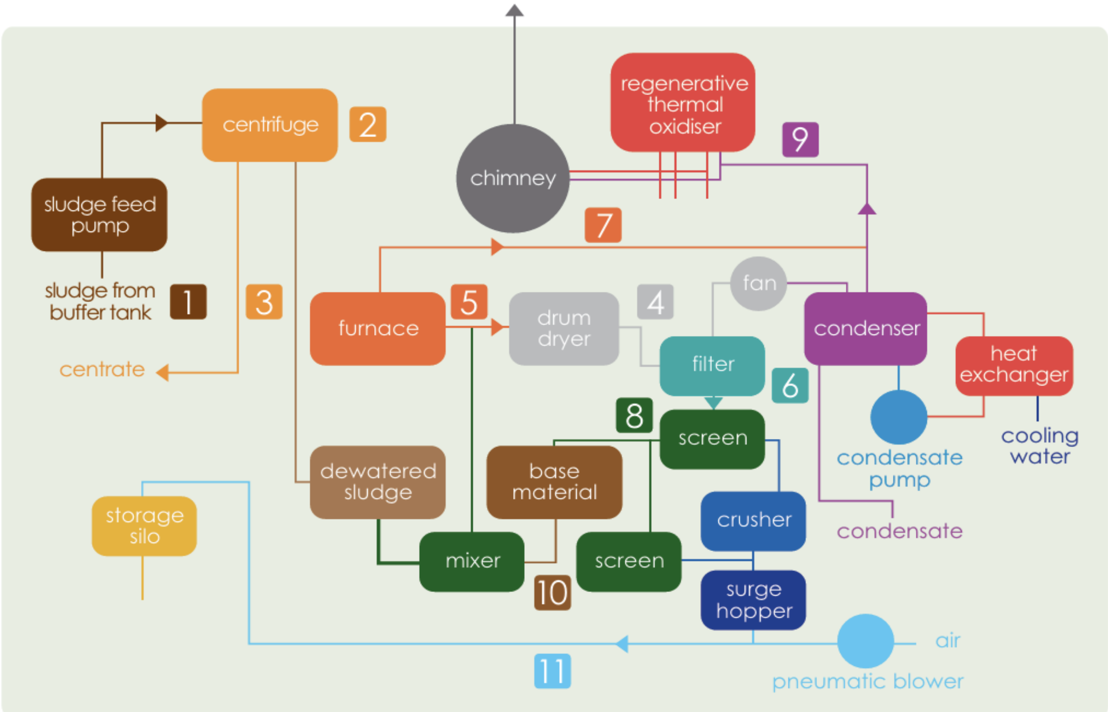


Adapted from Deviatkin [19]

Dried sludge has a number of applications. It can be bagged and used as material for composting or it can be incinerated to recover the energy in the organic matter. The following case study shows a plant in Daldowie Scotland that converts sludge to dried pellets, with the use of centrifuge and rotary drum dryers.

Case Study 1: DALDOWIE fuel Plant

Daldowie fuel plant is located in Uddingston near Glasgow, Scotland is one of the largest sludge drying centers in Europe. Commissioned in 2002 it has 12 centrifuges and 6 rotary drum dryers capable of producing dry low odour pellets. The facility reports that 1000 tons of sludge can produce 23.5 tons of pellets. The process schematic is shown below.



The figure below shows the pellets at the end of the process.

Incineration

Sludge with sufficient high DSC can be incinerated for final destruction with or without energy recovery. Incineration becomes autothermal (i.e. sustained by the heat generated by the combustion process) at DSC above 67%.

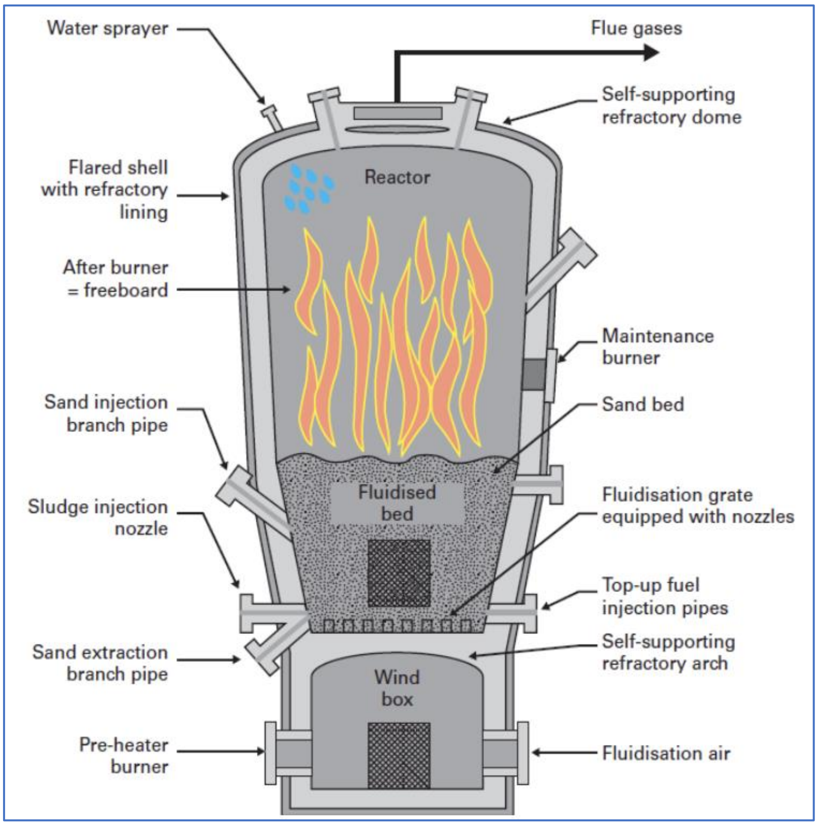
However, the generation of secondary pollutants such as dioxin, furans, NOx (oxides of nitrogen) and SO2 (sulphur dioxide), as well as dust particles, demands ancillary processes for removing these contaminants from the flue gas, adding to the overall cost.

Although most incinerators are energy-positive, the overall energy balance of the process is affected by the need to thermally dry the sludge prior to incineration.

Fluidised bed incinerator

Sludge incineration reactors are predominantly configured as fluidised beds (figure 41). Fluidised beds have a sand bed through which hot air is blown to form a fluid like bed to accept the dried sludge. Fluidised bed operates at a temperature of 800−900 °C and under atmospheric pressure. Particle retention times are in the order of two seconds within the reactor itself at the upflow air velocities of 0.5−1 m/s used.

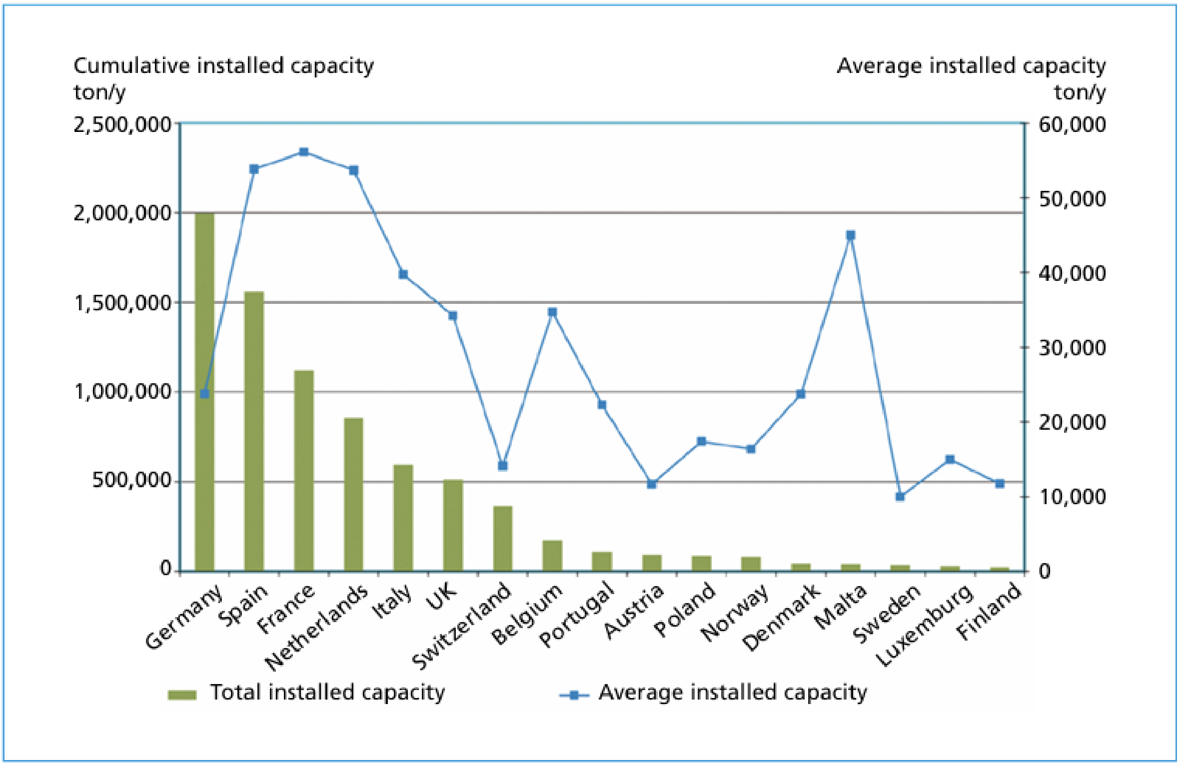
Figure 41: Example of fluidised bed incinerator



3.8 Case studies across Europe

In Europe Sweden has the smallest AD plant at 10,000 tons /year while the biggest can be found in France at 56,130 tons/year. Germany has the most AD capacity overall. This is shown in figure 42[7].

Figure 42 : AD capacity across Europe adapted (Luc De Baere and Bruno Mattheeuws)



Experience in Europe has shown that not all plants and technologies have been equally successful. Mixed or residual waste (residual waste is the waste left after source separate collection of the biowaste fraction) digestion is the most challenging as the feedstock poses the most problems due to the high level of contaminants in the organics. Below is another case study for a plant in the UK which produces refined methane and another in Sweden that produces liquid methane for use in transportation.

Case Study 2: Lanes Farm Energy -WELTECH Biopower plant, Yorkshire, UK

In 2019, the German biogas plant manufacturer WELTEC BIOPOWER constructed a large plant at Pontefract, West Yorkshire, UK for its client Lanes Farm Energy. The facility is for 80,000 tons of food and agriculture waste (cattle and chicken manure as well as grass silage and hybrid rye). The solids are fed through two walking-floor feed hoppers with 110 and 220m³, and two MULTIMix units, which removes foreign objects, liquefies, shreds and macerates incoming solids to make them into an easily pumpable, easily mixed, easily digested liquid. Liquids are fed in controllable volumes directly to digesters from five pre-storage tanks, of which two are equipped with a stainless steel bottom. Facility generates 7.3 million m^3 of gas annually (9600 households) in four stainless-steel digesters with a height of 8.8 m and an above-average capacity of 6,848m³ each. The raw biogas is refined efficiently in several stages and membrane upgrading is used to transform the biogas into high-quality biomethane. The digestate is stored in three digestate tank and are sold as high-quality fertiliser, returning organic material and nutrients to the land. For this purpose, it is first pasteurised and separated. The focus on sustainability is also reflected in these process steps. For example, the pasteurisation unit is equipped with a state-of-the-art energy-efficient heat recovery system.

For on-site electricity supply, the facility integrates a 500 kilowatt CHP. The operator generates additional income from exporting excess electricity to the grid. The facility took only 6 months to construct.

Case Study 3: Härnösand Energi & Miljö AB (HEMAB)

The biogas plant of Härnösand Energi & Miljö AB (HEMAB) in Sweden is about the size calculated for Seychelles. The plant was opened in January 2017 and has the capacity to treat up to 6000 ton of source sorted organic waste per year. Biogas is produced from food waste from Härnösand, Sundsvall and Örnsköldsvik. The produced biogas is upgraded to vehicle fuel quality, the upgrading capacity being approximately 5.2 GWh/a or 375 000 kg vehicle fuel yearly.

In the plant food waste is pre-treated by grinding, followed by anaerobic digestion in two serial digestion units, with the second digester having half the length/volume of the first digester. The produced bio digestate is separated in a liquid and a solid phase in a screw press. The solid phase is used for final covering of the local landfill and the liquid phase is currently being certified (SPCR120) for use by local farmers as fertilizer. The anaerobic digestion process is operated at mesophilic (39 °C) temperature in the first digester, while the second, smaller digester is used for plug flow hygienisation at 55–60 °C. Currently, the plant is prepared for being extended with a separate post-hygienisation unit for hygienisation at 70 °C for 1 hour. This will free up further capacity for mesophilic anaerobic digestion in the second digester.

4.Financial feasibility

For full scale plant, it is assumed that the gas produced will be converted to electricity as this is the cheapest and most profitable use of the gas given limitation for use of heat in the country.

4.1 Cost of AD plant (Scenario 1)

Table 5 below shows the cost of implementing such AD plant in Seychelles taking base figure of $400-$1500 per ton of wet waste, average $800 per tons of waste processed. It is assumed that the company will generate income from sale of electricity and a recycling (tipping) fee for processing waste that would otherwise end up on the landfill and paid for as a landfill disposal fee.

Table 5: Income and expenses for AD plant in Seychelles

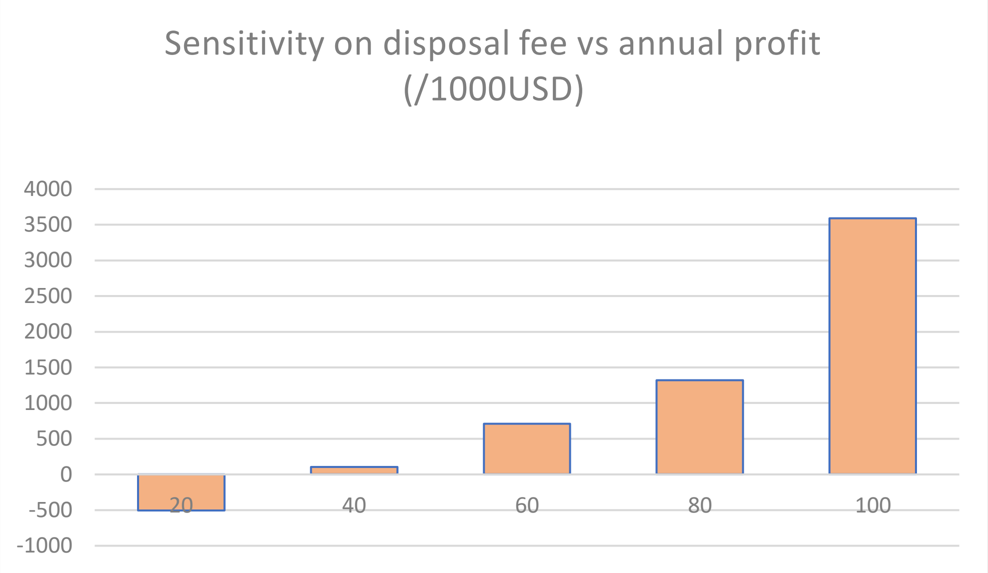
	USD	SCR
CAPITAL COST ($800/ton)	**28,637,600**	**429,564,000**
OPERATING EXPENSES	**2,571,655**	**38,574,820**
Staffing (3)	36,000	540,000
Annual Maintenance cost 2%	572,752	8,591,280
Utilities	6,000	90,000
Loan repayment (2.5% for 15 yrs)	1,956,903	29,353,540
INCOME	**3,409,664**	**51,144,964**
Electricity sale (SCR2.5/kwh)	1,261,844	18,927,664
Disposal fee ($60/ton)	2,147,820	32,217,300
GROSS PROFIT/ANNUM	**838,010**	**12,570,144**
TAX 15%	125,701	1,885,522
NET PROFIT	**712,308**	**10,684,622**

1m^3 methane is equivalent to 10kwh however efficiency is 40%

We see that an investment of USD 28.6 million will be required for 35,797 tons of bio waste per year and the net profit will be around USD 0.712 million. The contract cost is **$41.9 million** over 15 years. Selling cost of electricity is pegged at the high cost of SCR2.5 per kwh (unit) and include a recycling fee of $60 per ton. There may be possibility of creating and selling carbon dioxide gas and heat in addition to electricity.

Figure 43 shows how the net profit vary with changes to the recycling fee and we can see that near $70/ton recycling fee makes the venture interesting.

Figure 43: Sensitivity of recycling fee on profit.



This plant will be able to provide power to 345 households and save 276,569 litres of diesel annually used for production of energy. If we take the cost of diesel as $1.18 per litre then this equates to maximum savings of $326,351 per year. The cumulative saving over 15 years will be **$4million**. The net benefit is $4,000,000 -$41,900,000 = **-$37,900,000**. It is to be noted that this does not take into account the additional benefit for Government not having to create a landfill *to accommodate biowaste* for the next 15 years. We can include this cost (below).

4.1 Cost of reclamation and construction of a landfill

We assume that construction of a landfill requires land reclamation from the sea. For this amount of waste, the total void space required will be of order 875,000 m^3 (assuming compaction ratio of 1.2 tons/m3) which we can divide by the maximum landfill height of 20m to get a total area of 43,750 m^2. The landfill cost is estimated at $3 million (without leachate treatment) and total investment will be $14 million. Such landfill would also be able to accommodate all types of waste. This is summarized in table 7.

Table 7 : Cost for construction of biowaste landfill

	Voidspace m^3	Landfill area/m^2	Dredging cost $/m2	Total cost $
Dredging cost	875,000	43,750	250	10,937,500
Construction	Estimated			3,000,000
Grand Total				**13,937,500**

We see that the cost of a new landfill with reclamation will be around $14 million. The net benefit for AD replacement will be $13,937,500 -$37,900,000 = -$23,962,500. This is equivalent to net loss of around $1.6 million per year.

As expected, an AD plant is an investment over landfilling and offers an alternative which diverts organic waste from landfill reduce green house gasses and derive energy from the waste stream to reduce on imports.

4.2 Scenario 2: Sale of carbon dioxide

Now instead of burning biogas for energy, and wasting CO_2, the investor may separate and sell carbon dioxide in addition to burning methane.

We know the plant produces 3530.8m^3 CO_2 per day (40% * 8,827) and the density of CO_2 is 1.98kg/m^3. This is equivalent to 6.99 tons per day. Taking the cost of CO_2 as \$100 per ton, we get \$255,170 per year (or \$3,137,453 over 15 years).

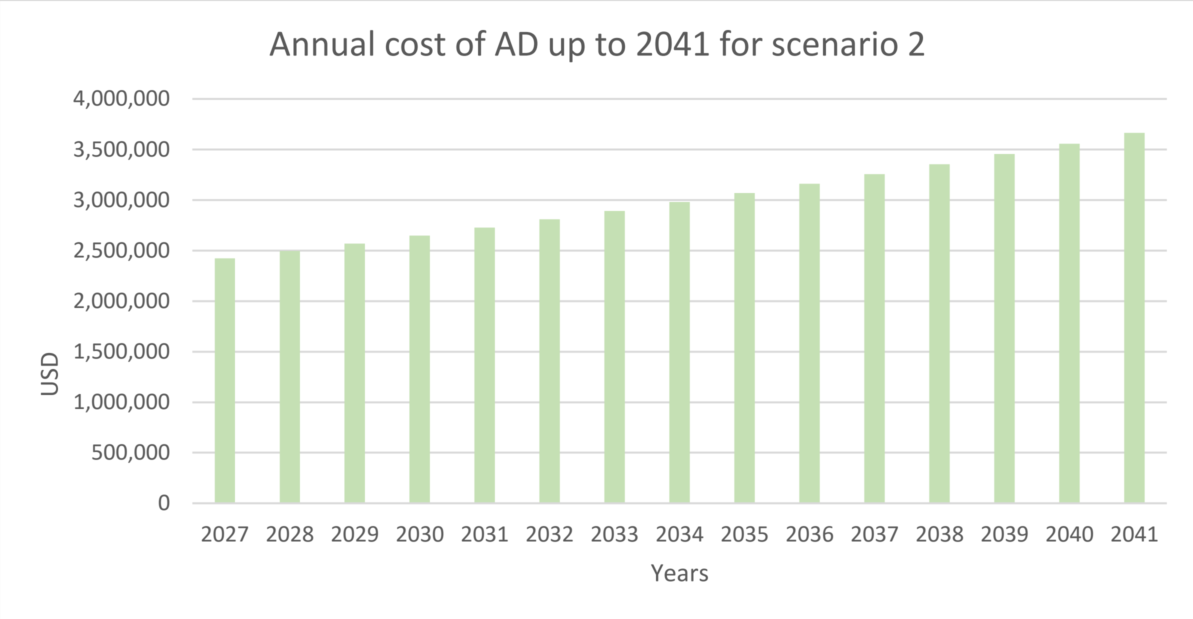
The methane will have higher heat capacity since it is pure so we can calculate a different Kwh. The volume is now 5,296m^3/day (60% * 8,827) and the energy rating for methane is 10kwh/m^3 and 35% efficiency equals 3.5kwh/m^3 This equals 6,765,896 Kwh per year. At SCR 2.5 per kwh we find this to be \$1,127,649 per year. So the profit changes to \$0.815 million per year as per table 8.

Table 8: Income and expenses with sale of CO2

	USD	SCR
CAPITAL COST (\$800/ton)	**28,637,600**	**429,564,000**
OPERATING EXPENSES	**2,571,655**	**38,574,825**
Staffing (3)	36,000	540,000
Annual Maintenance cost 2%	572,752	8,591,280
Utilities	6,000	90,000
Loan repayment (2.5% for 15 yrs)	1,956,903	29,353,545
INCOME	**3,530,640**	**52,959,602**
Electricity sale (SCR2.5/kwh)	1,127,649	16,914,739
Disposal fee (\$60/ton)	2,147,820	32,217,300
Sale of CO2	255,171	3,827,564
GROSS ANNUAL PROFIT	**958,985**	**14,384,777**
TAX 15%	143,848	2,157,717
NET ANNUAL PROFIT	**815,137**	**12,227,061**

The profit of the investor is a little more when separating the gas rather than just energy recovery. The sale of CO_2 will not be met by Government but rather is a third revenue stream by selling abroad or to local company such as Seybrew. Nonetheless the contract value is now worth **45.062 million** over 15 years (undiscounted) of which sale of CO_2 is \$3,137,453

Figure 44: Annual cost of scenario 2 up to 2041



We can think that the Government may want to negotiate a better price for electricity e.g. SCR 1.30 per kwh and disposal fee of $20/ton This situation is shown below

4.3 Scenario 3: Reduced kwh fee and disposal fee

We see that with the above changes, the contract is unsustainable. The income is not sufficient to meet the cost of operation.

Table 9: Income & expense at reduced cost to GOS

	USD	SCR
CAPITAL COST ($800/ton)	**28,637,600**	**429,564,000**
OPERATING EXPENSES	**2,571,655**	**38,574,825**
Staffing (3)	36,000	540,000
Annual Maintenance cost 2%	572,752	8,591,280
Utilities	6,000	90,000
Loan repayment (2.5% for 15 yrs)	1,956,903	29,353,545
INCOME	**1,557,489**	**23,362,328**
Electricity sale (SCR1.3/kwh)	586,378	8,795,664
Disposal fee ($20/ton)	715,940	10,739,100
Sale of CO2	255,171	3,827,564
GROSS ANNUAL PROFIT	**-1,014,166**	**-15,212,497**
TAX 15%	-152,125	-2,281,875
NET ANNUAL PROFIT	**-862,042**	**-12,930,623**

5 Summary & recommendation

5.1 Summary

Small scale investigations: The small-scale investigations showed that the kinetics of food waste degradation is consistent with what is reported in literature and follows the modified Gomperz model. It also showed that a continuous fed reactor works sufficiently well but works better when there is mixing, high temperature and when the pH is kept to around neutral. All this confirms what is reported in literature. The small scale also demonstrated design elements to follow for large scale reactor in particular the heights of inlet and outlet, most appropriate scrubber technique and gas pipe diameters and pressure to consider and safety aspect. The two months that were allocated to this provided valuable insight into the technology.

Small scale plant operation at domestic level: The technical feasibility for operating small AD plant in Seychelles is not very encouraging given the complexities involved in continuous operation of such plants and safety precautions that must be followed at startup. These plants in most instance will be unstirred and operated at sub mesophilic temperatures where they are not particularly efficient. In particular the small-scale studies showed that the reactors are prone to acidification which leads to a drop in biogas formation. This requires knowledge of the process which may not be available to householders and also the handling of caustic substances for neutralization which brings with it other potential hazards. If the plants have to be restarted, then air contamination is problematic and startup procedure closely followed to prevent explosion. All this means that the technology is difficult to implement in the domestic sector where LPG use is widespread and more advantageous and safer. However, there is scope for farms that have to deal with wastewater or manure waste and where AD plants offer a solution with biogas production as an additional benefit.

Industrial application: Large AD plants are technically viable for Seychelles since one is in operation and a footprint for a centralized facility can be accommodated in the Providence area. The amount of biowaste generated is sufficient to operate a medium plant capable of providing of supporting 264 households It can also accommodate condemned and expired foods that are landfilled however it will rely on inconsistent waste stream which can be problematic. A large AD plant requires specialist knowledge and full-time staff to operate and monitor the process. The technology work best with a consistent feedstock quality which may be difficult to control for municipal waste. An AD plant will not replace entirely landfill but will improve the general management of biowaste by avoiding greenhouse gas (GHG) emission from landfills and significantly extend its useful life. Currently IOT is operating an AD plant with primary focus for the treatment of fish waste -not energy production. The biogas is currently not being harnessed and the process is not without problems, indicating the complexity of maintaining high biogas yield. The existing facility would benefit from investment in a post primary digestion and sludge drying equipment to reduce the pressure on the Providence landfill.

Financial viability: As expected an AD plant will cost more than sanitary landfilling. For a total of up to 35,797 tons of bio waste in 15 years, the contract value is **$41.9 million** over 15 years requiring a disposal fee of $60 (SCR 900) /ton and SCR 2.5 per kwh. Additionally, the investor can get up to $45 million with sale of Co2**.** The investment can be attractive although better return can be obtained with $70/ton recycling fee. For Government, the option is a lot costlier than building a landfill even when taking into consideration savings on diesel for electricity generation and cost of reclamation and cost of construction of a landfill. It is to be noted that energy recovery operations from waste are generally much more expensive than other solutions since they require advanced technical input and machinery, are energy intensive and sensitive to operating conditions. It is why only more advanced industrialised countries have made advances in these technologies. For a Small Island Developing State, the challenges of engaging advanced treatment are as vulnerable as the context to which the SIDS find themselves, namely isolation; distance from main markets, limited technical capacity and financial means to afford and maintain advanced technologies.

5.2 Recommendations:

1. **Improvement to existing operation**: Since IOT has an AD plant, effort must be directed to better existing operating conditions by encouraging the company to invest in the equipment to increase the dry solid fraction of its digestate sludge so that it can be used for other means rather than disposing at the landfill. It can also work to obtain better gas yields. The IOT should be able to make use of the energy from biogas produced rather than flaring. They can invest in a biogas generator to feed electricity directly to the grid. However, it seems that there are as yet no provision by PUC to accept non-PV electricity generators and this should be seriously considered by the Energy Commission. The production of electricity from IOT biogas will reduce the demand for diesel for energy production and pressure on PUC generators.

2. **Study mixed feedstock**: The IOT is producing gas from a single feedstock i.e. fish waste which may not be the case for a large-scale AD plant accepting biowaste from different sources. Before adoption and or tendering, it is recommended that Government undertake study mission to countries that have experience implementing anaerobic digestion technology for municipal solid waste such as Denmark and the Netherlands. Similar visit could be done in Asian countries that have similar weather and feedstock. The study mission will confirm the suitability of the intended feedstock (food waste vs industrial biowaste), following which Government may consider launching a tender to design, build and operate a centralised AD plant in the Providence area.

3. **Domestic households:** There is still scope for small to medium plants, and these can be introduced on outer islands and on farms as well as other areas where treatment of waste is primary with possibility for energy recovery being secondary. There is good scope here. However, we do not recommend adoption of small AD plants at domestic level in the short term in view of the complexity of the process and safety around the production of flammable gas. These work well in rural application rather than more urbanized setting. For household application. the Government can build upon the work of TWENex to catalyse further investigations and research in small to medium AD plants in particular consider the question of mixed domestic waste.

4. **Education & training:** It is recommended that an education and sensitization programs including trainings be developed for small to medium plants operators and householders to increase uptake of decentralized AD units in location where it can be made possible. This can in the long term make small to medium plants feasible for domestic use. The project visibility will contribute towards this but must be sustained after end of project.

6. Annex

Annex 1: Calculating base concentration and volume to neutralize VFA in small scale

We assume that VFA can be represented by the acetic acid concentration. The pH obtained in the small scale at failure was 4.3. Therefore, the concentration of protons in the solution can be found using the equation $pH = -\log[H^+]$. The $[H^+] = 10^{-4.3} = 5.01\ x\ 10^{-5}$mol.dm^{-3}.

The reactor volume was 18 liters therefore number of moles of Hydrogen present is

$$n_H = 18\ x\ (5\ x\ 10^{-5}) = 9.02\ x\ 10^{-4}\ moles$$

The neutralization reaction is

$$CH_3CO_2H + NaOH \leftrightarrow CH_3CO_2^- Na^+ + H_2O$$

Molar ration 1:1 confirms that moles of NaOH required is $9.02\ x\ 10^{-4}$. So if we make up a **0.01 Molar** solution then

$$1\ mol\ NaOH \text{ is contained in } 1x10^5 ml$$

$$9.02\ x\ 10^{-4}\ mol \text{ is contained } in\ 9.02\ x\ 10^{-4}\ x\ 1x10^5 = \mathbf{90\ ml}$$

Mass of NaOH required for this 0.01M solution is

$$M = 40\ x\ 0.01 = 0.4g.$$

We needed to dissolve 0.4g in 1 litre and use 90ml to neutralize. However, noting that weak acid strong base will result in a buffer, the pH change will take a while to change. The acetic acid is a weak acid therefore after this neutralization takes place more acid will dissociate. It is necessary to find the total concentration of the acetic acid. This can be found by considering the dissociation of acetic acid

	CH_3CO_2H	$\leftrightarrow CH_3CO_2^-$	$+ H^+$
Initially	y	0	0
At EQB	y-x	x	x

Using acid dissociation constant $K_a = 1.8\ x\ 10^{-5}$ we solve the quadratic formula

$$x^2 = (y - x)(1.8\ x\ 10^{-5})$$

Plugging in the values we obtain

$$(5\ x\ 10^{-5})^2 = (y - 5\ x\ 10^{-5}) * (1.8\ x\ 10^{-5})$$

$$y = 1.89\ x\ 10^{-4}\ moldm^{-3}$$

Number of moles is therefore $1.89\ x\ 10^{-4} * 18 = 3.4\ x\ 10^{-3}$ moles

For 0.01M solution we needed a total volume of $3.4\ x\ 10^{-3}\ x\ 1x10^5 = \mathbf{340\ ml}$

Annex 2: Assessment of AD plant at Indian Ocean Tuna Ltd

ANAEROBIC DIGESTION OF FISH WASTE BY INDIAN OCEAN TUNA LTD IN SEYCHELLES

A visit was caried out on 24th October 24 at IOT. The factory is treating 1000 m^3 of wastewater daily through an activated sludge process. The wastewater first enters a coarse and then fine screener after which it moves to equalization anaerobic tank. Primary sedimentation is achieved with Dissolved Air Flotation (DAF) in the presence of a polymer. The wastewater then moves to an anoxic tank for denitrification before going into the aeration zone for BOD removal. There is recirculation between the tanks for nitrification in the aerobic tank. Secondary clarification is carried out with DAF and part of the sludge is recirculated to the aeration zone. The HRT in the aeration zone is 7 days and in the anoxic approximately 3 days.

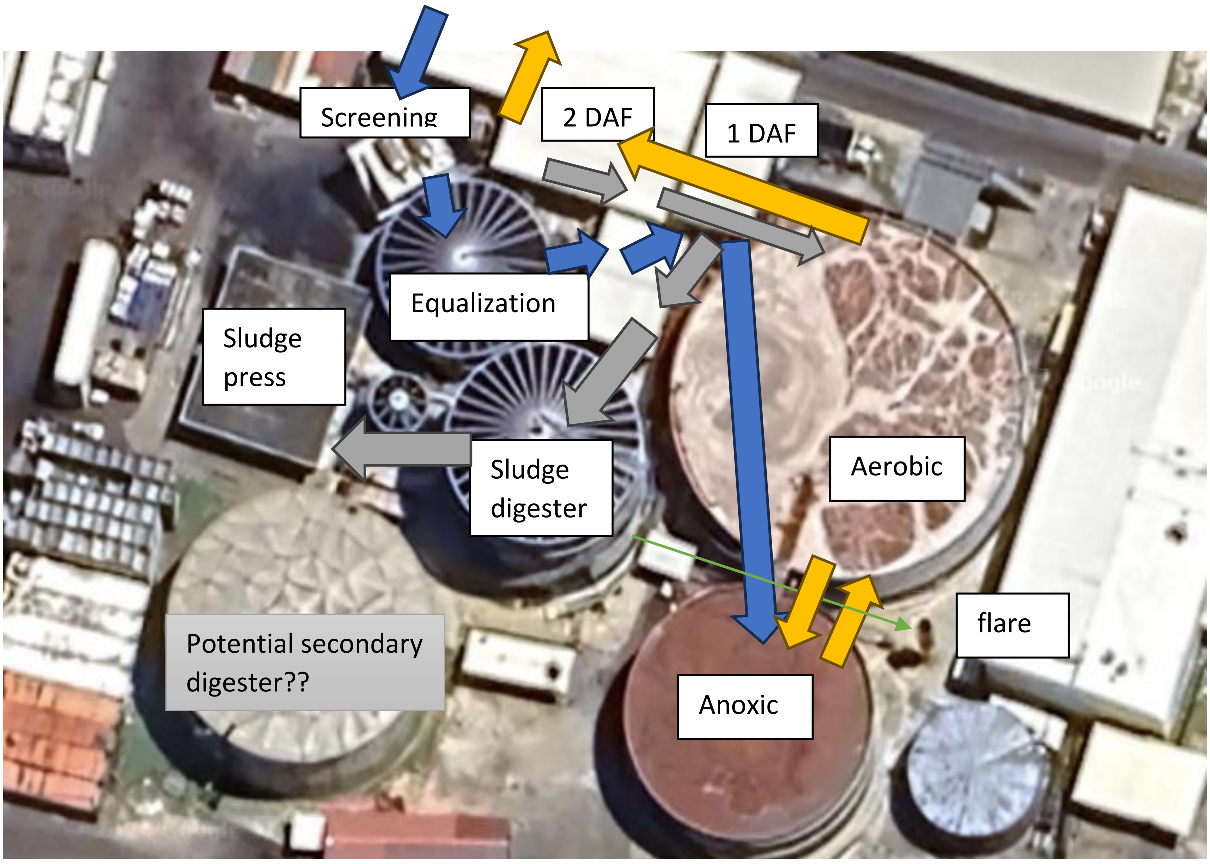
Sludge from primary and secondary DAF tank goes into a digester for anaerobic treatment producing biogas. The digester is operated at 35-40 degrees with mixing and hydraulic retention time of 20 days. Biogas produced is 2000m^3/day however in 2023 it was up to 4000m^3/day. The lower end production is equivalent to 1060 m^3/day of methane which equals to a potential electricity recovery of 2500 Kwh (2.5MWh) per day. The digestate is pressed in a screw press to remove water and the remaining sludge (10-15 tons/day) comprising of 80% water is sent to the landfill

The following issues was noticed

- The screener waste is fed to a chute and into bins which was not fully covered. There was some smell and fly lavae in the bins probably because it was not fully enclosed.
- The aeration tank was foaming suggesting the presence of filamentous bacteria and problems with process control. Low DO or FM can be the cause.
- The anoxic tank did not have much bubbling suggesting that denitrification may not be as efficient. It is possible that the nitrate in the wastewater is not high which is abnormal for this waste stream. This can only be confirmed by laboratory tests.
- There is one digester on site with HRT 20 days and the digestate leaving the tank is still strong. The facility will benefit from a secondary digester with HRT 30 days, however space seems to be problematic at the site. From photo below there appears to be a disused tank that can be used as a secondary digester. It may have been used in the past.
- The plant is operating at high mesophilic temperature / low thermophilic. It can be explored to operate near 55 C leading to faster degradation. There is concern that this will kill the bacteria however raising the temperature very slowly over time will get the bacteria acclimatized and thermophilic bacteria can then dominate. If ammonia inhibition can be avoided, the Biogas yield will increase and the digestate better degraded.

- The bio gas with high energy content is currently being wasted. It could be fed into a combined heat and power (CHP) plant to produce electricity and sold to the grid. The heat can be used instead of the boiler to keep the reactor to temperature and can be distributed to the cooking pots.
- It does not appear that the biogas is scrubbed of hydrogen sulfide and moisture. This will lead to damage of equipment over time. The flare was heard re-igniting the gas several times indicating that the flame dies out periodically possibly due to condensation problem.
- The sludge is too wet and LWMA indicated problems to accommodate it at the landfill. It is recommended that this sludge be dried to 20% before landfilling. Here the steam from the CHP plant can be used for drying. Presence of filamentous bacteria affects the dewatering step and this might be a contributing factor.

The photo below shows the wastewater flow in blue to treatment in orange and gray arrow represent the sludge.



SPECIFICATION

Anoxic tank D 20m H=9m V = 2827 m^3 HRT 2.8 days (Q=1000 m^3/day)

Aerobic D 30m H = 10 V = 7068 m^3 HRT 7 days (Q=1000 m^3/day)

Digestor D 16m H = 12m V= 2412 m^3 (Q=120tons/day solids) HRT 20 days

Gas production: 2000 m^3/d

Sludge production: 10 tons/day

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