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Community-based energy production from anaerobic digestion of biowaste

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Municipal solid waste is one of the greatest problems in the world, which causes not only different types of pollution in the earth but also various types of diseases. There are million tons of waste are produced every year. Hence, this huge amount of waste has to be safely disposed without causing any negative impact on the environment. On the other hand, world's economic and social developments mainly depend on the access of electricity. The conventional way (burning coal) of making electricity causes environmental problems such as GHG emissions and different types of air, water and land pollution. That is why, it is important to find a method by means of which the waste problem could be solved and, as a result, eco-friendly electricity could be gained.

Anaerobic digestion is the process where microorganisms breakdown biodegradable waste into smaller pieces in the absence of oxygen. By this process, it is possible to get electricity from biogas and compost for land. Consequently, anaerobic digestion can reduce pollution caused by organic solid waste and produce environmentally friendly electricity.

This thesis focused on producing energy by treating solid organic waste. The purpose of this thesis was to find a method that would solve both the waste problem and the energy production problem. A model was created for a community where the waste produced would be converted to energy. In order to reach this goal, several aspects such as a participatory waste management, anaerobic digestion system, plant design and sizing and emissions of gases were studied. As there are various types of wastes at the classification boundary, it was impossible to discuss other types of waste excluding organic waste in this thesis.

Keywords	municipal solid waste, pollution, diseases, GHG emission, electricity, microorganisms, anaerobic digestion system.

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Contents

1. Introduction

According to Local Government Engineering Department, Bangladesh [1], about 170 million people live in Bangladesh, 2637 people per square mile. It has eight divisions where about 14000 tons of wastes are produced every day. Out of this waste, 67.5% is organic waste [2]. This figure shows that there is huge possibility of producing biowaste to power. However, none of the cities of Bangladesh has a proper solid waste management system, right from collection to disposal.

As a consequence of unsafe disposal of waste, it occupies a huge area of land every year as well as causes various types of pathogenic problems for the people. With 100% collection efficiency, 273.21 acres of land is needed in Bangladesh per year [2]. As Bangladesh is a small country with a huge population, landfilling is not proper solution for it.

On the other hand, only 49% of the people living in Bangladesh have regular access of electricity [1]. Moreover, in the on grid area people suffer from blackouts for a few hours every day.

When it comes to the waste problem, most of the Western countries are trying to reduce waste generation as well as produce energy from it. Nowadays, different types of waste to energy technologies have been used to recover energy from waste. As a result of this, many countries are able to produce a good amount of energy in the form of biogas and electricity.

According to waste concern Bangladesh Ltd, municipality collects only 55% of total solid waste that is ended up in open dumping place [2]. It causes water pollution, odor pollution, various pathogenic problems and greenhouse gas emission.

This thesis focused on creating a model where proper waste management would be introduced in an area and it would be possible to produce power from the waste. The main objectives of the thesis were as follows:

- to introduce a proper waste management system in a model community.

- to show proper waste treatment that can solve various environmental and economic problems.
- to introduce community based power generation.
- to find out the process of generating energy from bio waste.

This thesis will help to develop a modern solid waste management system in Bangladesh, by means of which it would be possible to minimize waste-related problems and to generate more energy from waste.

2. Definition and characteristics of waste

Waste is a leftover or has low marginal value that the owners want to discard. On the other hand, it is merely raw material in the wrong place. Depending on how it is treated, it can be a burden or can be a free source for renewable energy or compost. There are many types of waste, and waste management systems are practised all over the world. However, in this thesis, the focus is on municipal solid waste (MSW) especially bio waste and its management system. The definition or the range of MSW varies country to country. Depending on the country, MSW may include:

- household waste
- household hazardous waste
- bulky waste from households
- street sweepings
- waste from institutions, commercial establishments and offices
- construction waste

2.1. Waste Management Criteria

There are no ideal waste management criteria, but it is always useful to identify some of the main criteria. The criteria that can be included in waste management are listed below [3]:

- providing a customized and robust handling of all waste with a minimum of effort for the customer and the citizen.
- ensuring the lowest possible load on the environment in terms of noise and contamination of air, water and soil.
- providing a maximum of resource recovery from the waste while minimizing use of resources in the waste handling.
- being a safe and healthy occupation for the workers offering no monotonous work and achievable challenges.
- respecting current laws, regulations and code of practice.
- being economically acceptable and fair.

2.2. Waste Hierarchy

The early 1980's, waste hierarchy has been used as the main approach to waste management in the Western world and parts of Asia. It is also known as 3R in Japan (reduce, reuse and recover) [3]. In waste management, the priorities should be:

- waste prevention and cleaner technology
- reuse
- recycling of materials
- recovery in terms of materials
- recovery in terms of resources and energy recovery
- disposal including landfilling and mass burning without recovery

Waste reduction means reducing the generation of waste. The definition of waste recovery includes the avoidance of a wasting product and the use of a long lasting product. Recycling of materials includes collecting and recovering certain materials (paper, glass, plastic product, etc.) to make a new product. Resources recovery involves the recovery of organic material from waste so that it can be used as soil nutrients and the conversion of waste to energy.

2.3. GHG Emission from Waste

Emissions from waste management must be counted as the sum of the individual process of the system. Emission from flue gas, dust and discharge of waste to air, water and soil are so low in mass that they usually do not appear in significant quantities but are still important in the environmental context. Therefore, emission accounts should be based on direct effluent emissions such as intended discharge e.g. stacks, sewers and filters, etc.) or disperse discharge (gases from composting piles, dust from a recycling facility or methane from soil composting). According to Kyoto Protocol, six greenhouse gases are identified; these are CO_2, CH_4, NO_2 and three fluorinated gases hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6) [4]. Figure 1 illustrates greenhouse gas emissions from different boundary conditions.

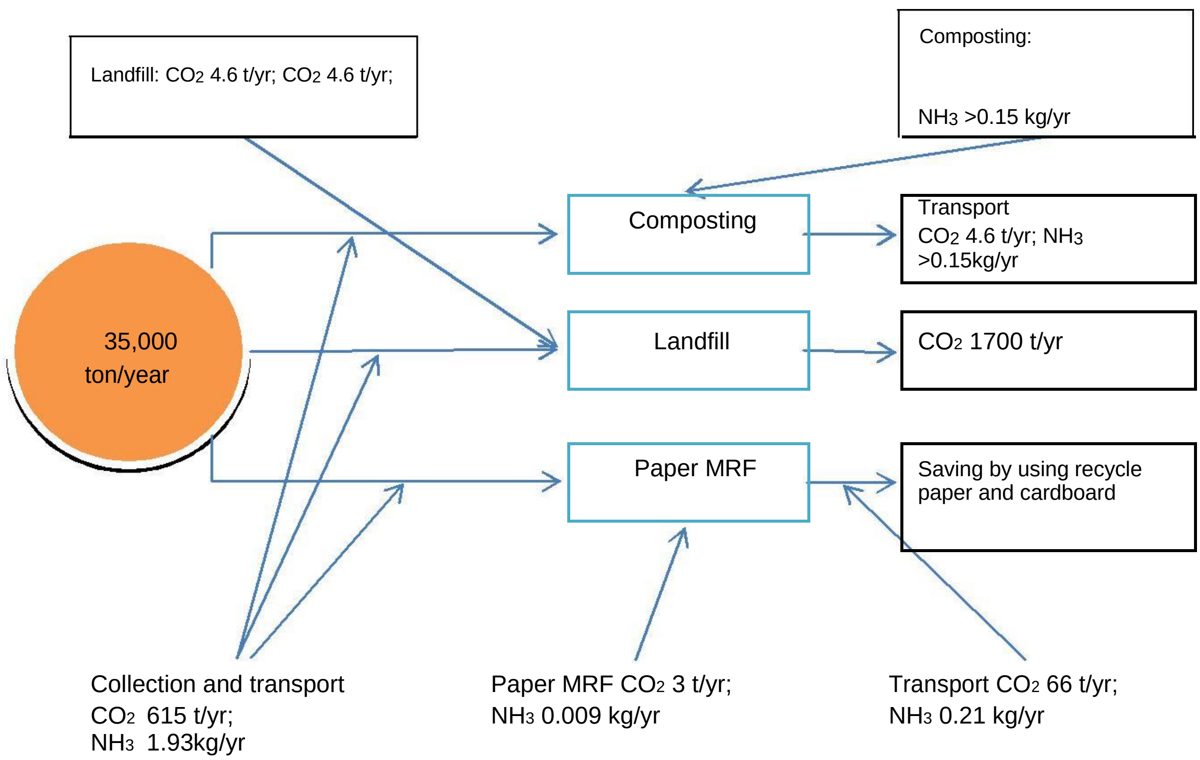

Figure 1. Emissions of a waste management system [3]

3. Anaerobic Digestion of waste

Anaerobic digestion may be defined as a biological process where organic matter is broken down to simpler components in the absence of oxygen. The overall result of anaerobic digestion is conversion of biodegradable of organic material into methane, carbon dioxide, hydrogen sulfide, ammonia and new bacterial biomass [5].

Different groups of microorganisms mediate different reactions with in anaerobic digestion. That is why anaerobic digestion is often termed as structured process. The different digestion processes are generalized in four steps:

a. hydrolysis

b. fermentation (Acedogenesis)

c. acetogenesis

d. methanogenesis

3.1. Hydrolysis

Hydrolysis is a reaction in which a large molecule splits, and hydrogen and hydroxide ions are attached to the separate products. This often occurs in the presence of an acidic catalyst. Hydrolysis is the first step of anaerobic digestion as it is commonly used to describe the lumped reactions in the solubilization of particulate compounds. Through hydrolysis, the large particulate compounds such as particulate carbohydrates, proteins and lipids are broken down into simple sugars, amino acids and fatty acids. Some of the hydrogen and acetate may be used by methanogens later in anaerobic digestion process. The rest of the large molecules must be broken down in the fermentation process.

3.2. Fermentation (Acetogenesis)

In the fermentation process, sugars and amino acids are converted into volatile fatty acids (VFA), alcohols, hydrogen, ammonia, H_2S and CO_2. Long chain fatty acids from the hydrolysis of lipids are not converted in fermentation but oxidized in the acetogenesis process. However, acidogenic bacteria break down the organic matter, but it is still too large to produce methane. That is why it needs to go through the acetogenesis process.

Figure 2 gives the stepwise degradation of organic matter.

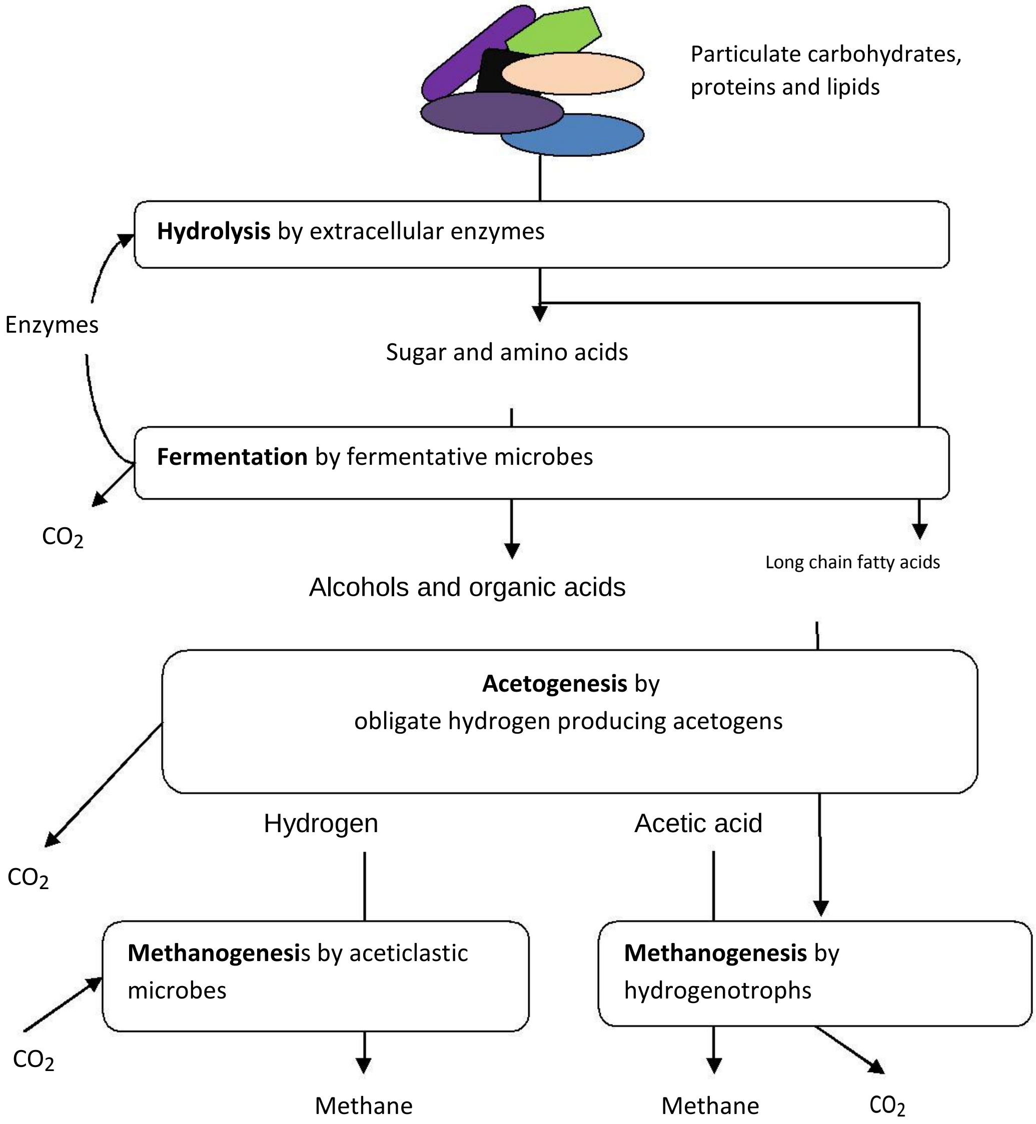

Figure 2. Stepwise degradation of organics to CH_4 and CO_2 [3]

3.3. Acetogenesis

Acetate, hydrogen gas and carbon dioxide can be produced through fermentation of VFA (such as propionate and butyrate) and alcohol (such as ethanol) by obligate hydrogen producing acetogens. By obligate means, there is no coupled reaction or external electrons available as electrons produced in this oxidation reaction are wasted into hydrogen ions to produce H_2. As more hydrogen gas is produced than other products, it is important to keep the partial hydrogen pressure low. Thus, it is necessary to remove a certain amount of hydrogen gas.

3.4. Methanogenesis

Methane gas is produced primarily by two pathways; hydrogenotrophic methanogenesis, which converts hydrogen and carbon dioxide into CH_4 and the aceticlastic methanogenesis, which converts acetate into CH_4 and CO_2.

Hydrogenotrophic methanogenesis takes place in close existence with acetogenesis and typically accounts for 30-40% of the methane according to this overall reaction:

$$4H_2(g)+CO_2(g) \rightarrow CH_4(g)+2H_2O(g)$$

Aceticlastic methanogene produces a biogas that is 60-70% methane. However, it is one of the most sensitive processes in anaerobic digestion. The overall reaction is as follows:

$$CH_3COOH(g)\rightarrow CH_4(g)+CO_2(g)$$

4. Process Parameters

In this part of the thesis, different parameters that affect the anaerobic digestion system are discussed. These parameters give indications of the process. They are easy to control and it is important to control these parameters to get optimum result.

4.1. Total Solid Content

Anaerobic digestion process can be classified according to total solid content of the slurry. Total solid content can be classified into three categories: low solid Ad system (usually less than 10% total solid), medium solid Ad system (has 15-20% total solid) and high solid Ad system (has 22-40% of total solid). Total solid contents decreases volume requirement of digester as it needs less water for digestion.

4.2. Temperature

Temperature has a strong influence on both physiochemical parameters and microbiological process. It determines the rate of hydrolysis and methanogenesis process. In addition, it has significant effect on gas transfer rates and settling characteristic of biosolids [6].

There are three generalized microbial operating temperature ranges. These are thermophilic (40-60°C), mesophilic (25-40°C) and psychrophilic (0-25°C). Viscosity decreases with increasing temperature. Increased temperature makes pumping and mixing easier. Thus, it improves mass transfer as well as gas-liquid transfer. The availability of solids generally increases. This is due to not only increased solubility of solids but also particulates such as fats may be melted.

Usually, low technological anaerobic digestion operates at psychrophilic temperatures due to the lack of heating of the digesters. The design decision is normally between mesophilic and thermophilic digestion. The thermophilic digestion provides a number of advantages compared to mesophilic digestions that are given below:

- reduction of the residence time in the plant
- good destruction of pathogenic organisms
- improved possibility for separation of solid matter from the liquid phase
- lower solubility of gases at higher temperature, which means that more gas in transferred to the gas phase
- improved solubility and availability of substrates

Essential disadvantages of thermophilic digestion compared to mesophilic digestion are listed below:

- demand of larger amount of process energy, or/and investment costs for heat exchanging and insulation.
- large risk of ammonia inhibition.

4.3. Retention time

The total time needed to complete degradation of organic matter is called retention time. It varies according to the process parameters such as temperature and waste composition. For example, mesophilic digester needs 15-30 days and thermophilic digester needs 12-14 days of retention time.

4.4. pH

Biogas production rate largely depends on the acidic condition of anaerobic digester. pH influences methanogens production rate. One of the most common overloads in anaerobic digesters termed as acid overload is related to pH, and it follows the self-reinforcing patterns:

- biostatic inhibitor, overload and other stress causes accumulation of acetate
- accumulation of acetate causes drop in pH (normally below 7)
- drop in pH inhibits aceticlasts, causing further accumulation of acetate
- further drop in pH, as well as accumulated acetate inhibits hydrogenotrophs and acetogens (pH drops below 6)
- system becomes fully inhibited and only acedogenesis can occur. Therefore, all the COD is converted to acids instead of methane (pH normally below 5)

As ammonia has a higher buffering capacity; for animal slurries and household wastes with high ammonia load, the pH can almost not decrease below 7. In these cases, the system does not fully break down but balances in an inhibited steady state condition, characterized by high VFA concentrations and low methane production yield. Most of the methanogens function properly with in the pH range of 6.8 to 7.5. However, their production rate decreases if the pH is below 6.2 or above 7.8.

pH values can be controlled by using some chemicals including sodium bicarbonate, potassium bicarbonate, sodium nitrate, calcium carbonate and calcium hydroxide. However, to avoid negative impact on bacteria, these chemicals should be added slowly. Calcium carbonate may be used to increase digester pH to 6.4, and carbonate salts should be used to decrease the pH to the optimum range [7].

4.5. Carbon and Nitrogen ratio

The bacterial growth inside anaerobic digestion process depends on organic carbon and nitrogen called C/N ratio. Higher C/N ratio is not suitable for optimum gas production and solid degradability. If methanogens consume nitrogen rapidly, a deficiency of nitrogen occurs. On the other hand, lower C/N ratio leads to ammonia accumulation and pH values over 8.5, which is toxic to methanogenic bacteria [8]. That is why it is important to maintain a C/N ratio with in optimum range of 20-30. It is possible to achieve a high C/N ratio component and a low C/N ratio product are mixed together. For example, organic waste is mixed with animal manure [9].

4.6. Mixing condition

Many solid co-substrates will require a size reduction treatment before insertion into the digester. The particle size of the co-substrate must be small enough to add and mix with manure properly. This requires a feeding system that will chop or grind the co-substrates. The substrates can be inserted directly into the digester tank using a dry matter input system, e.g., a funnel-shaped tank. Fluid substrates can also be inserted directly into the digester tank, possibly using the storage system.

4.7. Organic loading rate

Organic loading rate is the amount of organic matter that is treated in certain volume of digester with in a retention time. It is the measurement of biological conversion capacity of AD system. Higher organic loading rate causes system failure. Hydrolysis and acetogenesis bacteria produce fatty acid more rapidly than methanogenic bacteria produce methane gas from fatty acid. Thus, excess fatty acid leads to a pH drop and causes a system drop. In this case, the feeding rate must be stopped.

4.8. Inhibitory factors

Inhibition is a generalized term that means restriction of biological process. The inhibition process is divided into: (1) Toxicity, which is an adverse effect on microbial metabolism, and (2) inhibition, which is an important of bacterial function [10]. It is further clarified these terms as biocidal inhibition, biostatic inhibition and product inhibition [11].

4.8.1. Biocidal inhibition

Reactive toxicity is normally irreversible. By reactive toxicity, it is meant that the toxic compounds react with a functional component of the microbial cell, rendering it nonfunctional. Compounds, which are generally biocidal to some or all anaerobes, include detergents, cyanide and antibiotics. The technical difficulties involved with removal of the xenobiotics generally outweigh those caused by their toxicity to general anaerobic digestion.

4.8.2. Biostatic inhibition

Biostatic inhibition compounds are nonreactive toxicity and normally reversible. These compounds do not disable functional components, but rather disrupt cellular static, or change energy production. Microbes require intercellular conditions with redox potential, pH, and total salts with in a small margin. Biostatic inhibiting compounds disrupt these conditions, and the microbe is required to spend energy on maintenance of static, rather than anabolism. Free acids and bases (e.g., VFA's, H_2S, NH_3), salts, and pH changes all cause biostatic inhibition.

4.8.3. Product inhibition

A drop in free energy available from catabolism causes product inhibition. The most common product inhibition is hydrogen inhibition of acetogens even though acetate can also inhibit the same organisms at high concentrations.

5. Types of anaerobic digestion process

Depending on feedstock and need, many processes are available for anaerobic digestion. There are many factors that need to be taken into account before choosing a process, for example, feedstock type and volume, financial, and biological aspects. In this part, different processes are presented.

5.1. Dry / Wet Digestion

Anaerobic digestion can be wet digestion or dry digestion depending on the concentration of total solid of the feed substrate. A dry process has moisture content of less than 75% and the biomass looks like a thick slurry. The wet process has moisture content above 90%, where the biomass looks like a liquid.

The choice of moisture content in the process takes its starting point from the moisture content in the waste. High proportion of garden waste favors dry process, whereas liquid industrial wastes call for a wet process. However, also the management of the digest and issues related to ammonia inhibition may play a role. If a wet residue can be accepted as a fertilizer to be used on agricultural land, it favors a wet process. A high nitrogen content in the waste can lead to high and inhibiting ammonia concentrations in the factor and as water is used for dilution in the wet process such waste is best handled in a wet process.

Wet digestion process is designed to treat dilute slurry of less than 15% total solid content. If total solid content is more than 15%, then the appropriate solid concentration is maintained by adding liquid to the system or recirculating of liquid to system. In this system, mechanical mixing is necessary to break down the floating material. When this material is broken down into small pieces, there is more chance for digesting bacteria to mix with slurry. For this reason, wet digestion process usually takes place in stirred tank, where slurry is stirred by mechanical mixing or combination of mixing and biogas injection. However, this process needs pretreatment to remove heavy material so that it can not settle down at the bottom of the tank and decrease tank volume. This mechanical stirring and pretreatment makes this system costly compared to dry anaerobic digestion process.

The total solid content of a dry anaerobic digestion system is usually 15-40%. However, this system does not require addition of water as a wet anaerobic digestion system does, but to maintain a solid content of 30%, it is sometimes necessary to add some water. Pretreatment of this system is as complicated as that of the wet anaerobic digestion system.. Pretreatment is only used to remove coarse impurities via shredding or trommel screens. In a dry anaerobic digestion system, fermented waste moves to the digester through plug flow. It is necessary to mix incoming waste with fermenting biomass for adequate inoculation and to avoid acidification.

5.2. Continuous process

In the continuous process, post digestion tank is attached to the main digestion tank by a pipe. When substrates are added to the digestion tank, same amounts of substrate go to the postdigestion tank (Figure 3). The substrates that enter the post digestion tank are still able to produce biogas. That is why both the main digestion tank and the post digestion tank are sealed to collect gas.

The continuous process is suitable for farmers who want to store digestate for a longer period. In this process, the main digester can be constructed in small scale as it contains the digestate only for the duration of digestion. The digestate is mainly stored in the post digestion tank.

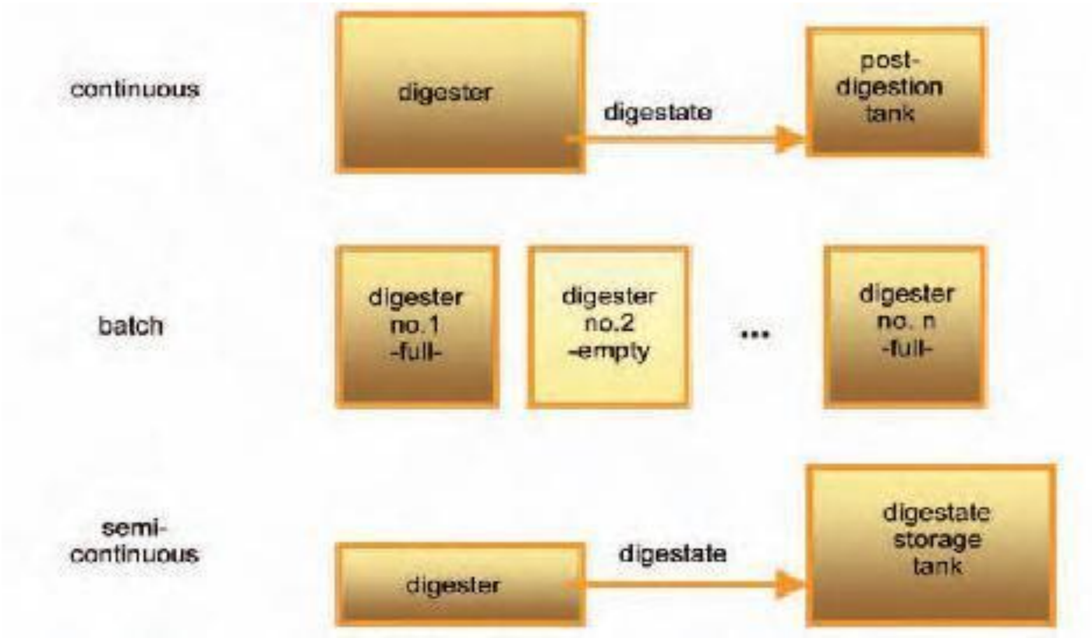

Figure 3. Schematic overview of AD processes Graphic [3]

5.3. Semi-continuous process

The semi-continuous process type of process is the combination of both batch and continuous process. In this process, substrates are stored in main digester as long as storage is required (Figure 3). Once it is filled up, the additional substrate moves to storage tank by an overflow. The disadvantage of this system is that the substrate can not be completely digested. For this reason, it minimizes biogas production rate compared to batch and continuous process.

5.4. Batch process

The third type of digestion process in batch process. In this process, several digester tanks are used to have continuous gas production (Figure 3). Once a digester tank is filled, it is sealed for a certain time. The gas production increases gradually over time until it reaches it peak. Once the production rate goes below certain level, up to 90% of digestate is then transferred to the storage tank.

6. Conceptual Case study in Tetly Union, Sylhet, Bangladesh

A rural place in Bangladesh was chosen to establish a model concept by which it may be possible to solve organic waste related problems. In this chapter, the present waste condition is discussed. Moreover, different possible sections of anaerobic digestion that can be used in this type of project are presented.

6.1. Area Profile

According to Local Government Engineering Department, Bangladesh, Tetly Union covers 20.8 km^2 of land with the population of 28,111 [1]. Most of the people in this area are either business or farmer. Moreover, in this area, they have five dairy farms consisting of about 250 cows and 8 poultry farms with about 900 chickens. The bio waste production of this area is 0.43 kg/person, where other types of mixed waste production are 0.2 kg/person.

Unfortunately, in this area, there is no waste management system. For this reason, the farms do not have hygienic environment as well as the households. They put the untreated biowaste in the open field to use it as a fertilizer. Therefore, it creates many problems including odor, mosquitos and flies, land problems and most importantly pathogenic problem. However, they have access to electricity and gas, but every day they have about a 2- to 3-hour black out. The above description applies not only to this particular area but also to the whole country of Bangladesh. That is why it is high time to take proper action to get rid of this problem.

The flow chart in Figure 4 describes how biowaste can be used for biogas production. At first, all of the collected waste will be sorted and chopped in desired size. After that it will be mixed with cow manure and poultry feed along with water with the ratio of 1:1. Next, it will transfer to digester for a certain time to digest. Then the digestate will move to post storage tank and meanwhile biogas will move to biogas treatment plant where it will be treated to use. From post digestion tank, the digestate will be sorted out to use as compost and leachate will transfer to mixing tank again. More details about this process is described later on this thesis.

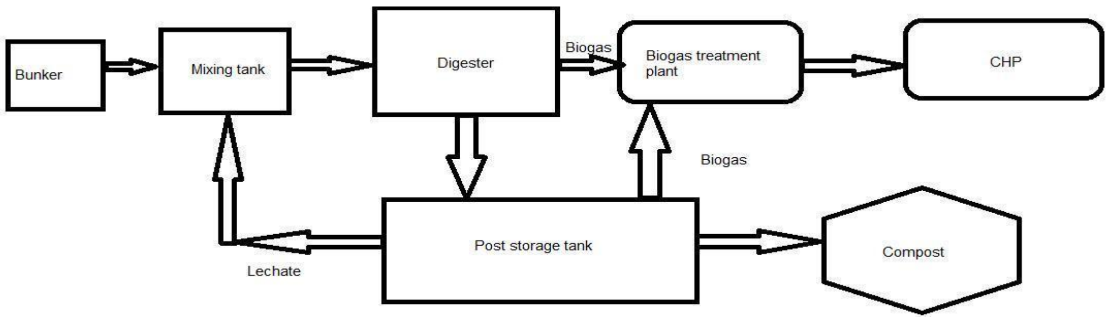

Figure 4. Flow chart of biowaste-to-biogas plant

6.2. Waste collection and pretreatment

To collect biowaste properly, it is necessary to introduce a proper waste collection system in this area. As the people are unaware of waste management systems, it is necessary to initiate public awareness program. In this program, field workers go to every house to talk with people about waste related problems and the benefits of waste management system.

Figure 5 shows how biowaste can be collected from every house. Every day people will put their biowaste in the waste bin, which will be transported to the waste treatment plant by a van. In the same way, the waste collecting people will collect cow manure and poultry waste from different farms.

Figure 5. Waste collection system [12].

The need for pretreatment of organic waste depends on the collected waste and other process steps. The pretreatment must be able to remove all the unwanted material from the arrival waste. It is not enough to select the pretreatment based on only an evaluation of the sorting criteria and collection system alone. Further economic considerations have a significant impact as any separation leads to the creation of a reject stream that can be very costly to eliminate and which contains organic material together with the material that has been separated. Different separation systems have different separation efficiencies, and the need and price for separating missortings have to be balanced with the loss of organic material. Typically, several steps are required in order to get sufficient reduction of missortings.

As this is a wet, one-stage, thermophilic process, no bag opening is needed as no bags are used in the collection system. The diminished material is transported on a conveyer belt and the foreign items removed by hand. Many substrates require a size reduction before entering into digester. It should be chopped around 2 cm particle size by stainless steel knife and mixed with manure before it feeds into digester(Figure 6). If the substrates are dry than it can be stored in funnel shaped tank and inserted directly into the digester tank. For fluid substrate, it is stored in storage system before inserted directly into the digester tank.

Figure 6. Co-substrate feeding system [13]

6.3. Hygienization

The plant does not include any separate hygienization step. The thermophilic digestion system itself is used for hygienization. Continuous plug flow in the reactor guarantees that all biomass stays in the digester for 13 days with an incoming temperature of 50°C. This type of hygienization is sufficient to allow agricultural use of the digestate in Bangladesh.

6.4. Piping for substrate transport

There are two types of piping systems; (a) pressurized piping, and (b) non pressurized piping. Pressurized piping is used for transporting substrate. For shorter distance of piping, the diameter of the pipe should be at least 100 mm. But if this is for longer distance, the diameter should be 150 mm. In order to prevent sediments on the bottom of the piping a minimum transport speed of about 1 m/s should be considered. Non-pressurized piping is subject to the influence of gravity. It requires a diameter of at least 200 mm. Commonly, the piping used for AD plants is made of steel. However, other materials such as plastics are also used [14].

6.5. Pump

In AD system, pumps are usually used for two reasons; it can serve to overcome a difference in height, or it can be used to drive a hydraulic stirring system. There are mainly two types of pump, these are centrifugal pumps and displacement pumps (Figure 7). To prevent the build up of sediments inside pumps, the piping is installed with a declining slope of 1-2%.

(a) (b)

Figure 7. Different types of pump; (a) Centrifugal pump, (b) displacement pump [13]

6.6. Stirring of digestate

Stirring of digestion is very important for several reasons, which are given below:

- balancing temperature in digester.
- mixing old and new substrate together to facilitate bacterial mixing with every portion of the substrate.
- preventing of the formation of layers.

Figure 8. Screw propeller [15]

A screw propeller system is suitable for a digester with volume of over 1000 m^3 (Figure 8). It consists of an electrical motor with a loading capacity of 2.5-25 kW. In a screw propeller system, height adjustment is necessary to prevent the creation of sedimentary layers.

In hydraulic stirring, the feedstock is sucked from upper part of the digester and sent back to lower part of the digester (Figure 9). The upper part and the lower part are adjusted in such a way that the feedstock mixes properly. The advantage of a hydraulic system is that there are no moving parts in the digester. The pump is located outside the digester and is thus easily accessible for maintenance [3].

Figure 9. Hydraulic stirring [13]

6.7. Digestion

Digestion takes place in a cylindrical shape container called digester. In digester, biomass is heated and stirred periodically. Stirring is important for proper mixing of old and new biomass and mixing of bacteria with organic material. It is also important for preventing sedimentation layers and maintaining even temperature inside digester. Stirring is also important in order to improve metabolism of the bacteria by removing the gas bubbles [5].

It can be made of concrete, steel or plastic. Steel made digester is comparatively expensive. That is why it is only used for laboratory purpose. Plastic made digester is cheap, but it is not durable for larger plant. On the other hand, concrete made digester is useful for every kind of plant. It is necessary to have a good insulation system for the digester to maintain the temperature. Most of the developing countries including Bangladesh use bricks for the digester. As an output, biogas and digestate are produced from digester.

6.8. Digester heating and insulation

As an anaerobic digester is proposed for the thermophilic process, it is necessary to heat the substrate up to the required level. In a vertical digester, heating pipes are installed inside digester wall (Figure 10). Sanitation tanks often use counter flow heating exchanger to heat the mainstream substrate up to 50°C by exchanging heat with sanitized substrate. However, in this case, there should be a thicker insulated wall.

Figure 10. Digester heating [13]

It is important to install an insulated wall for digester to reduce heat loss (Figure 11). There are many types of materials are used for insulation of digester, for example, mineral wool, mineral fiber mesh, polystyrene, and polyurethane foam or organic materials made from cotton, wool and cork.

Figure 11. Digester insulation [15]

Using of insulating material depends on the digester type. The thermal conductivity of different material influences the thickness of the wall. After insulating the wall, a top layer is required to protect the insulation from dirt and weather. The characteristics of different insulating material are given in Table 1 on next page.

Table 1. Characteristics of various insulation materials [3]

Insulation material	Density (kg/m3)	Heat conductivity (W/m K)
Polyurethane		0.030
Expanded polystyrene	20–45	0.040
Extruded polystyrene	30–80	0.035
Mineral wool	30–50	0.043
Cork	100–120	0.050
Sheep wool mesh	10–20 0.035	0.035
Cotton mesh	20	

6.9. End Products

Anaerobic digestion produces biogas and digestate as a final product. Biogas is a good source of renewable energy, which contains high amount of methane. Biogas can be used to produce electricity or heat. It can also be used for cooking. The another product of anaerobic digestion is odorless and hygienic digestate. It is a better fertilizer compared to untreated manure.

6.9.1. Biogas

Biogas is a good source of green energy. Its properties are similar to natural gas that is why it can be used as fuel. However, raw biogas contains some undesirable impurities that can hinder utilization of biogas as a renewable energy source. Biogas contains mostly methane (55-70 %) and carbon dioxide (30-45%). Biogas with higher methane content has higher energy level and thus increases the heating value. For example, 60% methane content of biogas has 6 KWh of heating value.

Biogas also contains 0-2% of nitrogen, 500< ppm of hydrogen sulfide and ~100 of ammonia. Ammonia, hydrogen sulfide and water vapor are known as trace components. Depending on the use of biogas, most of the time these trace components are removed for several reasons. Water vapor is corrosive for equipment when it reacts with acidic hydrogen sulfide or even carbon dioxide. Nevertheless, hydrogen sulfide is more poisonous and corrosive for gas piping and other instruments than water vapor. It even produces sulfur dioxide, which pollutes environment. That is why it is important to remove hydrogen sulfide from biogas.

Biogas production rate is different when using food substrates. Findings have shown that the use of different food substrates can cause differences in biogas production rates [5]. However, food substrates have different biogas production rates, but they vary over a range of approximately 20 to 480 m^3/t FM.. Figure 12 shows the changes in biogas production rates for each food substrate and the range in which biogas production can occur.

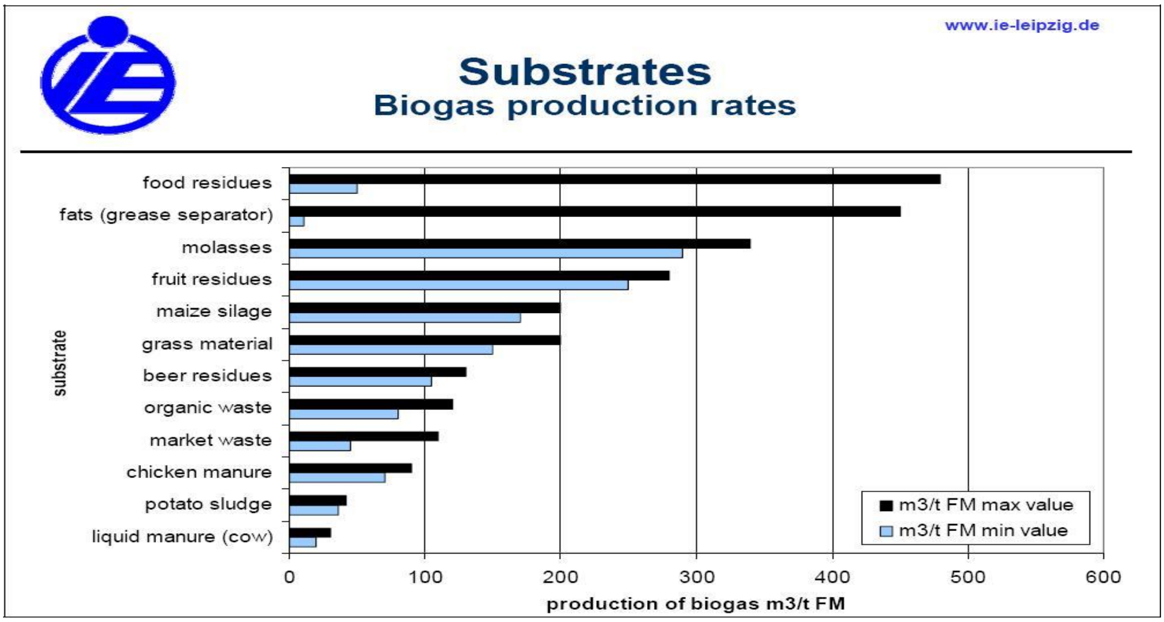

Figure 12. Potential Biogas Production Rates with Food Substrates [16]

It is noticeable that in some cases food wastes can cause a large increase of biogas production in comparison to cow manure. From the above chart, it is possible to determine a coefficient value in which the increasing biogas production rates of respective food substrates are compared to that of cow manure. Table 2 shows the coefficient values of different food substrates. By dividing each respective food substrate value (minimum or maximum) by the respective liquid cow manure value (minimum or maximum), it is possible to get a base value. This allows to make a correlation between the respective food substrate and comparable cow population.

Table 2. Coefficient ranges of different food substrate [10]

Substrate	Coefficient Range	
	Lower	Higher
Cow Manure	1.00	1.00
Potato Sludge	1.20	1.45
Chicken Manure	3.60	4.00
Market Waste	2.50	4.40
Organic Waste	4.50	4.80
Beer Residues	5.20	5.25
Grass Material	7.50	8.00
Maize Silage	8.00	8.75
Fruit Residues	11.60	12.50
Molasses	13.60	14.50
Fats	0.25	18.00
Food Residues	2.50	19.60

6.9.2. Biogas Storage

There are two purposes for biogas storage. (1) on-site use, and (2) off-site use. In practice, most of the biogas is used right after its production. In this case, a smaller volume of storage is required. But, sometimes biogas is stored to use only for peak electricity demands. For this case, comparatively a larger volume of tank is required.

Depending on the operating pressure, three types of storage tanks are used for storing biogas. Low-pressure storage tanks are least expensive and easy to store biogas. The energy, safety and operating system make intermediate and high pressure storage system costly. These storage systems are discussed in more detail below.

- low-pressure storage

Low-pressure storage systems typically operate at pressures up to less the 2 psi. Floating gas holders are typically used for this kind of storage systems. It is made of steel, fiberglass or a flexible fabric. As it does not react with H_2S, the least expensive and trouble free gas holder is flexible fabric top (Figure 13). High-density polyethylene, low-density polyethylene and linear low-density polyethylene are used as flexible fabric material. The typical thickness of the materials vary from 0.5 to 2.5 mm.

- medium-pressure storage

Medium-pressure storage system operates between 70 to 300 psi. Weighted gas bags or floating roofs are used for medium-pressure storage tanks. Reinforced and non-reinforced plastics or rubbers can be used to make this kind of storage tanks. It is important to remove H_2S from biogas prior to enter storage tanks to prevent corrosion and safety. The typical volume of this kind of storage tanks vary from 880-28000 ft^3.

- high-pressure storage

High-pressure storage system operates between 300-4500 psi. Gas scrubbing is important at high-pressure storage system to remove impurities such as H_2S and water. Steel tank is usually used for this kind of system. Storage system must be adequately equipped with safety devices such as rapture disks and pressure release valves.

Figure 13. Internal biogas storage [17]

6.9.3. Biogas treatment and utilization

It is important to remove impurities from the gas such as carbon dioxide, hydrogen sulfide or moisture before using it in applications. Three applications with increasing demand for gas treatment are common:

• Power and heat production: Power and heat production is the most common application for biogas utilization. The requirement to pretreatment is moderate and simply consists of removal of water and hydrogen sulfide. Biogas contains about <500 ppm of hydrogen sulfide (H_2S). This gas is corrosive and poisonous. Therefore, it is important to remove hydrogen sulfide from biogas. This can be done by adding some air (2–6 volume %) into the upper part of the digester, close to the biogas outlet. Oxidizing bacteria will convert the hydrogen sulfide into sulfur, after which it will drop into the digestate as elementary sulfur. When the amount of air is dosed correctly, the amount of H_2S in the biogas can be reduced by 95%. However, if too much air is added the elementary sulfide will convert into sulfuric acid. Furthermore, the combination of air and biogas can be very explosive. Therefore, it is very important to control air supply.

Figure 14. Desulphurization [13]

- Vehicle fuel production: Upgrading of gas to vehicle fuel requires higher methane content. It is obtained in the digestion process. Beside water and hydrogen sulfide, most of the carbon dioxide must be removed to reach a methane content above 95%. Different commercial processes exist for such upgrading. Pressurizing the produced biogas is needed when it is utilized as a fuel for traffic [18].

- Upgrading of biogas to natural gas quality: Upgrading of biogas to natural gas quality requires even higher methane content than biogas for vehicle fuel. Different technologies are under development, but they are expensive and only used in few cases.

6.9.4. Digestate

Digestate is a nutrient rich substrate, which is produced from anaerobic digestion. Even though digestate and compost have similar characteristics, it is not compost, as compost is produced by aerobic micro-organisms. Digestate is full of nutrients with volume of 90-95% of what was feed into digester. All the nitrogen (2.3 - 4.2 kg/tonne), phosphorous (0.2 – 1.5 kg/tonne) and potassium (1.3 – 5.2 kg/tonne) present same in the digestate as none of them are present in biogas. The nutrients of digestate are more bioavailable than raw slurry meaning it is easier for plants to make use of these nutrients. Digestate is transferred to the post digestion tank (Figure 15) to be stored until the digested substrate can be used. These tanks are usually covered in order to avoid nitrogen losses and to collect the additional biogas that forms during storage of the digestate.

Figure 15. Post-digestion tank [13]

6.10. Odor Control

Organic solid waste itself can give rise to serious smell problems as the waste sometimes can be up to two weeks old when it arrives at the biogas plant. Especially during warm periods, heavy smell problems can be experienced. Furthermore, the anaerobic process itself and especially production of hydrogen sulfide can cause problems. Malfunction of other processes such as the composting of the digest may also cause problems. Almost all existing plants experience smell problems now and then and some have been closed down due to unsolved smell problems.

Solving odor problems from biogas plants involves a lot of air that needs to be cleaned; the concentration of problematic substances is low but many different smelly substances are present. Consequently, the solution of odor problems starts with reducing the risk of odor production by keeping a good and smooth handling of the waste. Raw waste shall not stay untreated for long periods and good control of the process shall be kept. Areas with risk of odor problems shall be separated from other areas in order to keep the amount of smelly ventilation air down. In many cases, waste is delivered in a closed building, the processes are to the greatest possible extent performed in close tanks, and complete treatment of ventilation air from buildings or tanks is needed. Five main systems for odor treatment are in use [3]:

- Dilution of the ventilation air

The simplest way to reduce odor problems is to dilute the ventilation air. It is easily done by discharging air through a chimney. Only minor odor problems can be solved in this way, but a chimney is often used as the last step in combination with some of the other methods.

- Incineration

Incineration is very effective but at the same time expensive as a lot of air needs to be treated and the contents of substances are low. Incineration is seldom used but can be used for treatment of ventilation air from smaller, very smelly areas.

- Catalytic oxidation

It is a new technology for odor control. The addition of the catalyst accelerates the oxidation and enables a lower operating temperature (250-500°C) than incineration. The metal catalyst normally used is expensive but the operating costs are low for low combustion temperature.

- Biological filters

Biological filters utilize microorganisms and convert inorganic substances such as hydrogen sulfide and ammonia to less problematic substances. The basic idea is to create a large surface for growth of microorganisms. If the ventilation air is brought in contact with the microorganisms, significant degradation and conversion takes place. The water content plays a significant role, as the microorganisms need water in order to prevent dry out. Too much water lead to poor oxygen transport to the biological degradation and clogging of the filters. In practice, many biological filters are used. Most common are compost and bark filters (or mixture of the two materials). Such filters are inexpensive and provide a good support material for a great variety of microorganisms.

- Chemical scrubbers

In chemical scrubbers, the air is first washed under acidic, then under alkaline conditions, and finally with addition of oxidizing materials (hypochlorite), this is shown to be an effective and robust solution, but the construction and operational costs are high.

From above odor control methods, the best one is to use biological filters for its inexpensive and easy utilization. Air from both mixing tank and digester passes a biofilter with outlet through a high chimney before it is released to the environment. In this way odor can be controlled.

6.11. Measurement and control equipment

There are several measurement devices that help a biogas plant to run the system efficiently. They control the performance of various components and detect any misbehavior of the system. The most important measurement devices are as follows (Figure 16).

Figure 16. Measurement equipment [18]

- Temperature Sensors

Temperature Sensors are attached to the digester wall to measure the temperature of the digestate. They also measure the consumption of produced heat. If they are attached to the flow meter, they can measure generated heat and processed heat simultaneously.

- Substrate level indicator

It is important to know the amount of substrate level and substrate flow. By measuring the substrate level, the substrate level indicator helps to assess the performance of the digester and thus the amount of biogas produced.

- Electricity meters

Two electricity meters are required: one is to measure the internal consumption of the system and another one is to measure the electricity delivered to the grid [3].

- Gas meters

At least two gas meters are required; one for gas production and another one for gas consumption. The gas meter is important for safe operation of the system.

6.12. Safety equipment

Handling of biogas is always dangerous; thus requires safety rules in order to minimize risks of accidents. There should be safety equipment installed and accident prevention regulations must be followed in biogas plant. An overview of safety equipment is given in Figure 17 below:

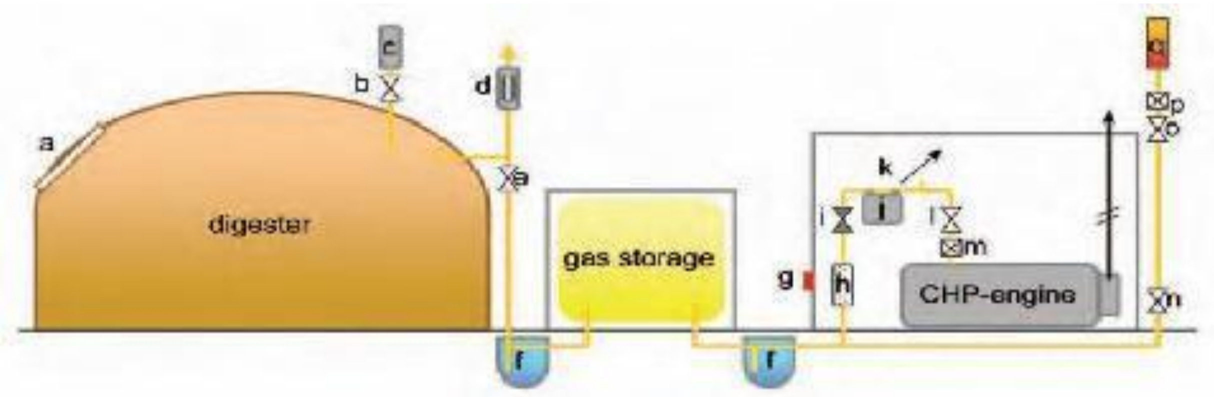

Figure 17. Overview of biogas system safety components [3]

The components are as follows:

(a) manhole
(b) back-pressure valve
(c) air dosing pump
(d) safety/blow valve
(e) check valve
(f) condensate trap
(g) panic button
(h) gas fine-mesh filter
(i) vacuum pressure switch
(j) gas metre
(k) pressure gauge
(l) self-closing valve
(m) flame trap
(n) check valve
(o) self-closing valve
(p) flame trap
(q) flare

It is important to maintain the distance between the digester, the CHP engine and the stables or other buildings. There are also safety measures that can be addressed in the design of the biogas plant. For example, tank openings should be large enough to ensure sufficient ventilation; check valves and other safety switches must be easily reached; all the gas piping needs to be corrosion-resistant (copper piping does not fulfil this requirement); and the housing of the CHP engine needs to be adequately ventilated to provide a sufficient rate of air change [3].

7. Sizing calculation

It is important to calculate the size of different components of anaerobic digestion (AD) system to estimate the investment costs. The following sections will present the formula that can be used to calculate the required volume and size of the various components.

7.1. Volume calculation for digester

Digester volume calculation is based on the thermophilic process. That is why the temperature was taken 50°C. The digester volume was calculated on the basis of a recent survey. This formula is taken from biogas project, LGED, Bangladesh [14].

- Cross section of a digester (Figure 18)

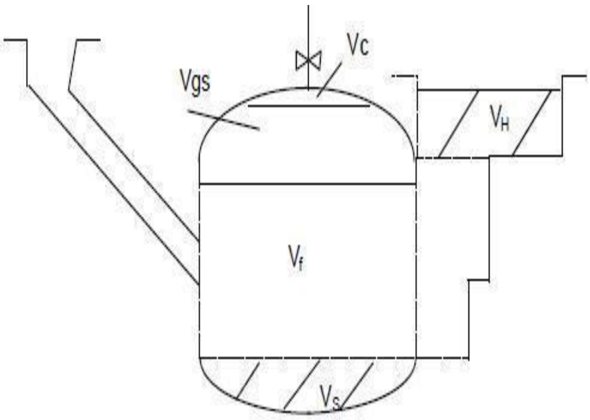

Figure 18. Cross section area of the digester

Total volume of digester was calculated as follows:

$V = V_C + V_{gs} + V_f + V_S$

a) V_C = Volume of gas collecting chamber
b) V_{gs} = Volume of gas storage chamber
c) V_f = Volume of fermentation chamber
d) V_H = Volume of hydraulic chamber
e) V_S = Volume of sludge layer

- Geometrical dimensions of the cylindrical shaped biogas digester body (Figure 19)

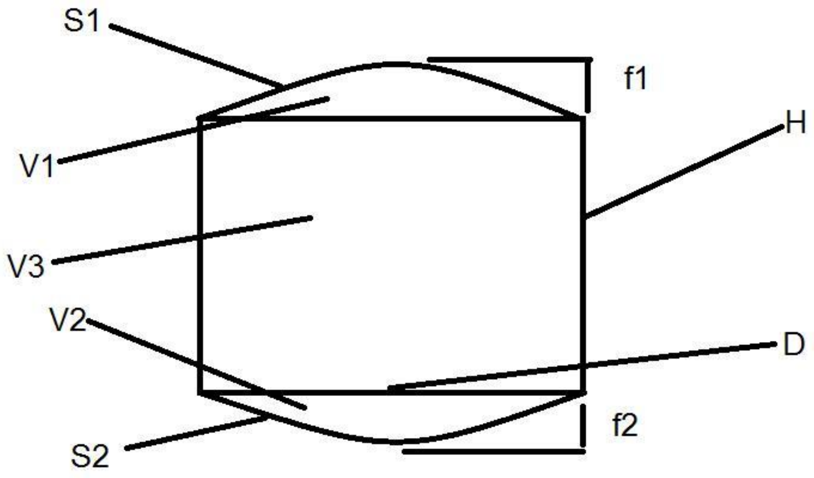

Figure 19. Geometrical dimensions of the cylindrical shaped biogas digester body

a. The following formula were used to calculate volume:

$V_c < 5\% V$

$V_{gs}+V_f = 80\% V$

$V_s < 15\% V$

$V_{gs} = 0.5(V_{gs}+V_f+V_s)K$

where, K= Gas production rate per m^3 digester volume per day. For Bangladesh K=0.4 m^3/day.

b. The following formula were used to calculate volume:

$D= 1.3078\ V^{1/3}$

$V_1=0.0827\ D^3$

$f_1=D/5$

$V_2=0.05011\ D^3$

$f_2=D/8$

$V_3=0.3142\ D^3$

$S_1= 0.911D^2$

$R_1=0.725\ D$

$S_2=0.8345\ D^2$

$R_2=1.0625\ D$

The following data were used for calculating the working volume of the digester:

- hydraulic retention time (HRT) = 13 days (for temperature 50°C)
- Cow population= 250 cows
- Production of cow manure= 2.50 ton/day (approximately from recent survey)
- organic waste generation= 8.45 ton/day (approximately from recent survey)
- Total discharge = 10.95 ton/day
- Water and substrate volume ration is 1:1

So, the total inlet (Q) is calculated multiplying total discharge by 2= 10.95*2 ton/day = 21.91 ton/day = 21.91 m^3/day (1 ton= 1 m^3).

The following formula can be used to calculate the working volume:

Working volume digester (Vgs+Vf)= Q*HRT = 21.91 m^3/day* 13 days = 284.91 m^3
Vgs+Vf= 0.80V

Total volume (V) = Vgs+Vf/0.80 = 284.91/0.80 m^3 = 356.14 m^3

Total diameter (D) = 1.3078 $V^{1/3}$ = 1.3078 * $(356.14)^{1/3}$ = 9.09 m= 10 m (approximately)

Again, V_3= (3.14 * D^2 * H) / 4 (Putting V_3=0.3142 D^3)

So, the height of the digester (H) = (4 * 721.5) / (3.14 * 122) m = 3.63 m (approximately)

7.2. Post-digestion storage

The following formula is used for sizing digestion storage tank:

Size of storage (m^3) = Annual input substrate (m^3/yr) * required storage time (months)/ 12 – total volume of digester (m^3).
21.91 m^3 * 365 days= 7997.15 m3/yr of cow manure and substrate is digested for a retention time of 13 days. A storage time of 1 month is required. So, the size of post storage tank can be calculated as follows:

Size of storage (m^3) = 7997.15 m^3/yr * 1/12 – 284.91 m^3 = 381.51 m^3

7.3. Biogas production

The following formula shows how to calculate biogas production using only cow manure:

Biogas rate = Comparable cow population * manure rate * volatile solids (%) * methane conversion rate * 1/CH4 (%)

By substituting the following values in the above formula, it is possible to calculate the potential biogas production rate. It is important to note that, AD system is possible to operate with in three temperature range; psychrophilic, mesophilic and thermophilic. Though it is expensive to operate AD system in thermophilic process, it is able to produce greater methane content with shorter retention time. As stated before, this thesis is based on thermophilic temperature range.

- Cow Population = 250 cows
- Volatile Solids (VS) = 8.5% = 0.085

Methane Conversion Rate (for the respective temperature range):

Thermophilic (~50°C) = 0.29 L CH_4/ g VS= $2.9*10^{-4}$ m^3 CH_4/
g Assume Biogas Methane Percentage (CH4%) = 62%
Biogas rate (m^3/hr) = 250 cows* 101604.66 g/hr * 0.085 * 0.00029 m3/g * 1/0.62 =
4544,56 m^3/hr = 4544,56 m^3/hr * 8760 hr/yr = 39810315,36 m^3/yr

The Table 4 shows the numerical relationship between biogas values and cow population. As cow population is independent variable and biogas production is dependent variable, there is a linear relationship between cow population and biogas values.

Table 4. Biogas Production Rates with cow manure

Cow population	Mesophilic with Dairy Cow Manure Biogas production (m3/hr)
210	3817,43
220	3999,21
230	4180,99
240	4362,77
250	4544,56
260	4726,34
270	4908,12
280	5089,90
290	5271,69
300	5453,47
310	5635,25
320	5817,03
330	5998,81
340	6180,60
350	6362,38
360	6544,16
370	6725,94
380	6907,73
390	7089,51
400	7271,29

Figure 20 displays the linear relationship between cow population and the biogas production rates.

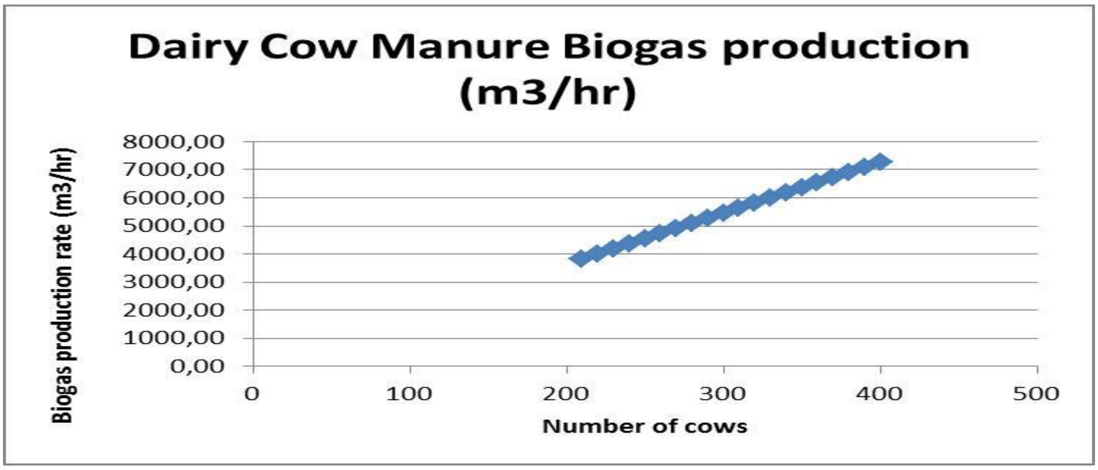

Figure 20. Biogas Production Rates with Dairy Cow Manure

The following equation is used to calculate the lower and upper range of biogas production of specific food substrate in relation to a comparable cow population.

Biogas rate from substrate= Comparable cow population * manure rate * volatile solids (%) * 1/CH4 (%) * substrate coefficient * methane conversion rate

The above equation is similar to previous equation except that is multiplied by the respective substrate coefficient (lower or upper boundary). Multiplying with substrate coefficient, results in an increase in biogas production rate. For food substrate, lower and higher substrate coefficient values are respectively 4.5 and 4.8. This provides a relationship between cow manure and the amount of biogas production of respective food substrate.

Sample calculation for the Biogas Rate using organic waste:

- (lower Value) Biogas rate (m^3/hr) = 250 cows* 101604.66 g/hr * 0.085 * 0.00029 m^3/g * 1/.62 * 4.5 = 83.86 m^3/hr = 20450.504 m^3/hr * 8760 hr/yr = 179.15*10^6 m^3/yr.

- (higher Value) Biogas rate (m^3/hr) = 250 cows* 416.66 g/hr * 0.085 * 0.00029 m^3/g * 1/.62 * 4.8 = 89.45 m^3/hr = 21813.87 m^3/hr * 8760 hr/yr = 166.2*10^8 m^3/yr.

7.4. CHP capacity

The following formula can be used to calculate CHP capacity.

CHP capacity = (Biogas production (m^3/yr) * calorific value of biogas (MJ/Nm^3/3.6)) / (operational full load (hr/yr) * electrical efficiency

Average calorific value is 22 MJ/Nm^3. As a rule of thumb, an electrical efficiency of 30% is used. If the CHP unit is used full-time, the number of operational hours will be around 7500.

CHP capacity (kWe)= ($166.2*10^8$ m^3/yr * 22 MJ/Nm^3) / (7500 hr/yr * 30%) = $162.5*10^6$ kWe /yr.

7.5. Insulation of digester wall

The insulation of digester wall can be calculated by:

Area of wall insulation = Digester height * Digester diameter * π = 3.63 m * 10 m * 3.1416 = 114.03 m^2.

If the insulation is 6 cm thick, than the volume is: 0.06 m* 114.03 m^2 = 6.84 m^3.

8. Conclusion

Municipal collection of organic waste is irregular and unavailable in many places in Bangladesh, including the study area of this thesis. Moreover, most of the local people are not concerned about the bad effects of untreated bio waste. Almost all of the farmers in Bangladesh use untreated cow manure as fertilizer. Therefore, they do not get optimum result from cow manure.

Biowaste to energy is a comparatively new technology for Bangladesh. There are a few NGO’s, who are working on the composting of biowaste, but none of them is considering the conversion of biowaste to energy. This technology is becoming popular all over the world because it not only treats bio waste but also gives compost and power as output.

The aim of the study was to establish a conceptual model by which problem related to organic waste can be solved, and simultaneously some output can be gotten. In this thesis, it was not possible to include compost production rate for lacking of data. However, from the conceptual case study it is found that $162.5*10^6$ kWe /yr of electricity can be produced from biogas. It is possible to produce more electricity, when dry compost can be used in the burner instead of using it as a fertilizer.

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