Lesson 32

Title of the Experiment: Generation of biogas from degradable organic wastes
(Activity number of the GCE Advanced Level practical Guide - 70)

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Introduction:

One promising technology that can successfully treat the organic fraction of waste is anaerobic digestion. Anaerobic digestion (AD) of degradable organic matter is of increasing interest in order to reduce the emissions of greenhouse gases. This is achieved greatly by capturing emitted gas and utilization via combustion thus converting it to CO_2 and obtaining energy as well. Bio gas is a versatile renewable energy source that can be used for replacement of fossil fuels in power and heat production as these conventional energy sources are being depleted. Methane rich bio gas can also be used to replace natural gas as a feed stock for producing chemicals and materials. In addition, this also provides nutrient rich liquid organic fertilizer for the improvement of soil fertility.

In developing countries, the promotion of biogas systems has been largely targeted towards the rural household sector. But in developed countries, the emphasis is different. In developed economies, this technology has been utilized successfully and effectively at large scale in sectors such as industrial and urban waste treatment. Quite large systems have entered into commercial operation and large cities are planning to switch to compressed bio methane for its transport fleet.

The utilizable feedstock for AD therefore vary depending on the application. Municipal solid waste (MSW), sewage sludge, agricultural waste, industrial waste and animal by-products are some of the organic materials that can be used as feedstock for AD. Organic waste from households and municipal authorities provide potential feedstock for anaerobic digestion. The source separation of MSW provides the best quality feedstock for AD. Digestion of sewage sludge provides significant benefits when recycling the sludge back to land. This is also considered an important step since it produces renewable energy and improves the ability of the sludge to settle which makes it easier to dry. On the other hand, digestion of animal manure (eg. Cattle manure) is probably the most widespread AD application worldwide. In some developed countries, the easily degradable wastes are becoming scarce and farmers are looking for alternative substrates (energy crops) such as corn, barley, rye or grass. In Germany the income from electricity produced from biogas made from corn is higher than using the same crop to feed fattening beef. Further, organic solid wastes from industry are increasingly treated in biogas plants. For example, AD of industrial waste waters is becoming a standard technique.

Theory:

Anaerobic digestion processes rely upon the microbiological degradation of organic waste in the absence of molecular oxygen. Therefore, the process is performed in a closed digester or bioreactor cell, associated with optimal conditions for bacterial digestion. The process can be divided into "wet" and "dry" digestion depending on the total solid concentration of the feeding substrate. In the wet process, the total solid concentration of the substrate is less than 15% and in the dry process, it is between 20-40%. In general, both anaerobic processes are considered a proven technology for the treatment of organic solid waste.

The AD is a complex process which can be divided into four phases: hydrolysis, acidogenesis, acetogenesis and mathanation (Figure 1).
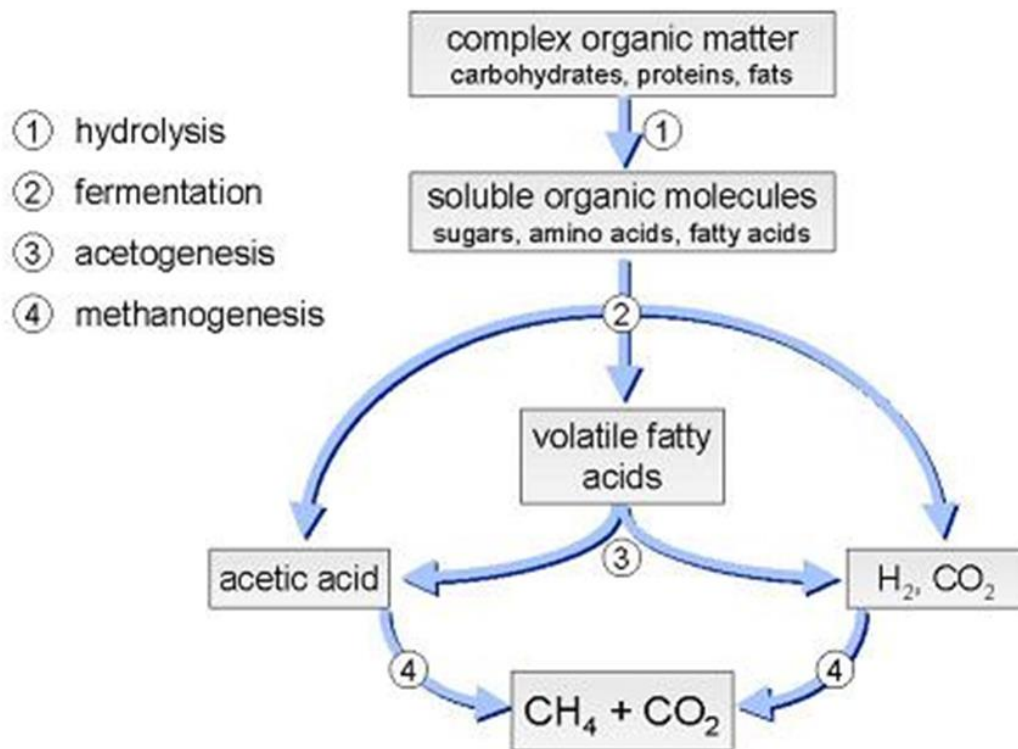
Figure 1: Pathways for mineralization of organic matter to biogas in an anaerobic digestion process (Source: Diltz R and Pullammanappallil P (2013))

Hydrolysis (Liquefaction)

The first stage of anaerobic digestion is hydrolysis. This process depolymerizes the insoluble polymers (carbohydrates, cellulose, proteins and lipids) and liquefies into monomers (sugars, amino acids and long chain fatty acids). Polysaccharides such as cellulose, starch, and pectin are hydrolyzed by the extracellular enzymes cellulases, amylases, and pectinases, secreted by *Clostridium, Acetovibrio, Celluliticus, Staphylococcus and Bacreroides*. Proteins are generally hydrolyzed to soluble peptides and amino acids by proteases and they are secreted by *Bacteroides, Vibrio, Clostridium, Bacillus, Proteus vulgaris,* and *Peptococcus.* Lipases convert lipids into long-chain fatty acids. *Clostridium, Staphylococcus* and the *micrococci* appear to be responsible for most of the extracellular lipase producers. Hydrolysis is a rather slow and energy consuming process and it is considered to the overall rate limiting step.

Acidogenesis

In the second step of the anaerobic degradation process, the products of hydrolysis are degraded to produce long-chain organic acids (propionic acid, butyric acid, valeric acid), short chain fatty acids, alcohols, organic nitrogen compounds, organic sulfur compounds, carbon dioxide and hydrogen. The intermediate products are generated by hydrogen producing and facultative anaerobic acedogenic bacteria (E.g.; *Desulfovibrio, Syntrophbactor* and *Syntrophomonas*). In addition, the produced acetate is directly consumed by methanogenic bacteria while others are undergoing acetogenesis.

Acetogenesis

The long chain fatty acids are converted to formic acid, acetic acid, carbon dioxide, and hydrogen while low molecular weight volatile fatty acids are converted to acetate. This conversion is done by acetogenic bacteria (E.g.; *Clostridium* and *Syntrophomonas*). However the main acid products of the both acidogenesis and acetogenesis processers cause to falls the pH level of the digester. On the other hand, the proportion of acid products is largely depending on presence of particular acid tolerable bacteria.

Methanogenesis

Methane is produced from raw materials of previous acidogenesis and acetogenesis by obligate anaerobic methanogenic bacteria (E.g.; *Methanobacterium* and *Methanobrevibacterium*). It is undertaken by acetate decarboxylation of acetic acid (66% of methane production), methanol reduction with hydrogen and reduction of carbon dioxide with hydrogen (34 % of methane production). By reducing the partial pressure of hydrogen, methanogenic bacteria stimulate the acetogenic bacteria to produce acids. Methanogenic bacteria are pH sensitive species that tolerate in mildly acidic conditions

Biogas is about 20% lighter than air. It is an odourless and colourless gas that burns with blue flame similar to Liquid Petroleum (LP) gas. The composition of bio gas produced by anaerobic digestion primarily includes methane (CH_4) and carbon dioxide (CO_2), with smaller amounts of hydrogen sulphide (H_2S) and ammonia (NH_4)(Table 1). Trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), saturated and halogenated carbohydrates and oxygen (O_2) are occasionally present in the bio gas.

Table 1:-Composition of bio gas

Component	Concentration by volume
methane (CH_4)	55-60%
carbon dioxide (CO_2)	35-40%
Water (H2O)	2-7%
hydrogen sulphide(H_2S)	20-20 000 ppm
ammonia (NH_4)	0-0.05%
hydrogen (H_2)	0-1%
nitrogen (N_2),	0-2%
oxygen (O_2),	0-2%

The performance of anaerobic digestion process is influenced by many physiochemical and biological factors such as the characteristics of substrate, temperature and pressure, pH, C:N ratio, hydraulic retention time and organic loading, mixing condition and inhibitory substances.

The characteristics of substrate:

High bio gas production potential and degradability of solid waste determine the successful anaerobic process and basically they are dependent on the amount of the main ingredients. Among them, lipids are the most significant substances in the anaerobic process, since the methane yield from lipids is higher than from most other organic materials. On the other hand, it was also found

that the lowest hydrolysis rates were obtained in the assays fed with kitchen waste that contained an excess of lipids. The other ingredients such as lignin and ligno-cellulosic waste which are readily available in garden waste are considered to be quite resistant to anaerobic digestion. Since hydrolysis is the rate limiting step in the overall process, several pre-treatment methods of ingredients such as thermal (adding steam) or chemical (addition of lime, acid or ammonia) have been suggested in certain systems.

Temperature and Pressure:

Temperature determines the rate of anaerobic digestion primarily the rates of hydrolysis and methanogenesis. The process of anaerobic fermentation and methane forming bacteria works best in the temperature between 29°C to 41°C (mesophilic) or between 49°C to 60°C (thermophilic) and pressure of about 1.1 to 1.2 bars absolute. Mesophilic bacteria can tolerate greater changes in the environmental parameters while thermophilic process offers high gas production rates and pathogen removal. But, the latter is more sensitive to toxic substances and changes parameters. If enough adaptation time is allowed, the selected populations at 30, 37, 40, 50, 55^{0}C will produce bio gas at similar rates (Figure 2 dotted line). The biphasic curve is a result of insufficient adoption and selection time by increasing the mesophilic and lowering the thermophilic temperature and not awaiting several retention times. The rate of gas production increases with the increase in temperature but the percentage of methane reduces. From the energy point of view, the thermophilic process is considered as less attractive as it requires more energy for heating. It is found that temperature between 32°C-35°C is most efficient for stable and continuous production of methane. Biogas produced outside this range will have a higher percentage of carbon dioxide and other gases than within this range of temperature.
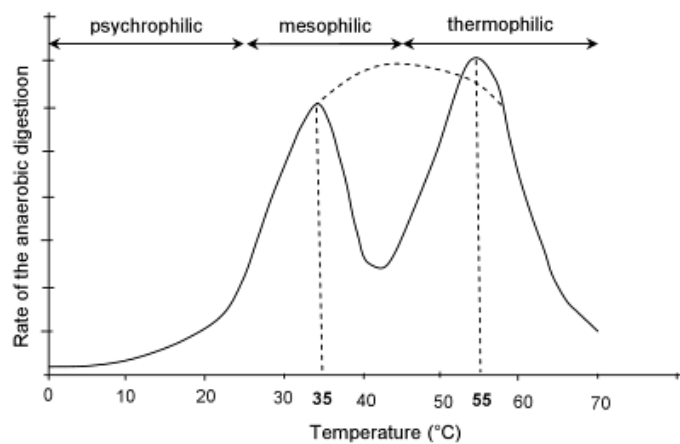
Figure 2: Effect of temperature on the rate of anaerobic digestion

(Source: Mata- Alverez (2002))

pH:

The pH of the materials is an important indicator of the performance of the digester. Metabolism of microbes is greatly influenced by pH variations in the digester. For a smooth enzymatic activity of acid forming bacteria, pH needed is about 5. But methanogenesis proceeds only at a high rate when the pH is maintained at 7. The rate of methane production therefore, may decrease if the pH is lower than 6.3 or higher than 7.8. pH in anaerobic digestion can be adjusted by adding some chemicals such as sodium-bi-carbonate, potassium –bi-carbonate, calcium carbonate(lime),calcium hydroxide (quick lime) and sodium nitrate slowly to the digester.

Carbon to Nitrogen ratio:

The relationship between the amount of carbon and nitrogen present in organic materials is presented by C:N ratio. In general, optimum C:N ratio in a digester is between 20 and 30. A high value is an indication of a rapid consumption of nitrogen by the methanogens. This may yield a lower gas production. The low value on the other hand indicates accumulation of ammonia in the system. Most probably this will show a high pH vale (about 8.5). Optimum value can be achieved by mixing waste of low and high C:N ratio (eg. Organic solid waste mixed with animal manure).

Hydraulic retention time:

This is a measure to explain the average time that a certain substrate resided in a digester. In a continuous mixing type digester, the reactor contents have a relative uniform retention time. If this time is shorter, the system will fail as the washout of the slowest growing micro organisms that are necessary for the anaerobic process. This shortening consequently reduces size of the digester and yields a higher bio gas production rate but less degradation of organic matter. The retention time for a dry anaerobic system ranges between 14 and 30 days and for a wet anaerobic system it can be less than 3 days. The organic loading rate is the amount of organic matter that must be treated by a certain volume of anaerobic digester in a certain period of time. If the organic matter concentration is relatively constant, the shorter the hydraulic retention time the higher value of organic loading rate is achieved. The potential risk of the increase in organic loading rate would be that the hydrolysis and acidogenic bacteria would produce intermediate products rapidly. Therefore, accumulation of fatty acids may lead a pH drop causing the system failure.

Mixing condition:

Mixing helps prevent the thermal stratification and the formation of a surface scum buildup in the digester as it provides sufficient contact between the fresh substrate and viable micro organisms. This also enables the release of produced bio gas from the content in the digester while reducing the particle size. However, vigorous and continuous mixing may course inhibitory actions as the disruption of syntrophic relationships.

Inhibitory substances:

The digestion process may be failure due to the presence of certain toxic materials in the digester. These toxic substances can be found as components of feeding substrates or by-products of the metabolic activities of the micro organisms. Among these, ammonia, light metal ions, heavy metals, sulfides and organic substances can be identified.

Ammonia is a product of hydrolysis formed during anaerobic digestion by degradation of nitrogenous materials in the digester. The inhibition occurs due to the change of intracellular pH, inhibition of specific enzyme reactions and the increase of maintenance energy requirement to overcome the toxic conditions.

The light metal ions that are available in the digestate of digesters are sodium, potassium, calcium and magnesium. They may be produced by the degradation of organic matter in the feeding substrate or some times by chemical addition for the pH adjustments. Although the moderate concentrations are helpful to active the system properly, high levels of these light metals may be toxic to the system.

Presence of heavy metals in trace amounts may stimulate the growth of anaerobic digester's flora. The heavy metals such as Cd, Pb, Hg are non or less biodegradable. They can accumulate to potentially toxic concentrations. The heavy metal toxicity in anaerobic digestion depends upon the various chemical forms in the digester. The toxicity may influence to interactive a wide range of enzyme function and structures by replacing naturally occurring metals in prosthetic groups of enzymes.

Some of the important organic substances that are responsible for the inhibition of anaerobic digestion are chlorophenols, halogenated aliphatic, nitrogen substituted aromatic, long chain fatty acids and lignin compounds. The toxicity of above substrates may vary widely and is affected by many parameters including biomass concentration, cell age, feeding pattern, acclimation and temperature etc.

To overcome inhibitory actions of anaerobic digestion, several strategies have been suggested. Some of them are removal of toxic substances from the feeding substrate, addition of chemicals to precipitate or insolubilize feeding substrate, change of the chemical form of inhibitory substances through pH control etc.

Anaerobic digesters can be classified into several categories as single stage, multi stage and batch. The temperature range of digestion, mesophilic or thermophilic as well as the solid content also explain the type of reactor used.

In single stage processes, all stages of AD process occur in one reactor and are separated in time (eg. one stage after the other). The technology behind the multistage process is improving AD by having separate reactors for the different stages. In general, two reactors are used, first for hydrolysis to acidogenesis and the second for methanogenesis.

In batch systems digesters (Figure 3) are filled once with fresh substrate and allowed to go through all the degradation sequentially in the dry mode. In here, the leachate collected from the bottom of the reactor is continually re-circulated.

Figure 3: A batch type digester established in Dikovita- Sri Lanka

Learning outcomes:

At the end of the section, the student will be able to;

- name and describe the functions of each part of a domestic bio gas unit/digester
- prepare the organic materials that are needed to produce bio gas in a domestic bio gas unit/digester
- determine the quantity of materials that is needed to add into the digester and the frequency of adding of materials
- maintain the bio gas unit
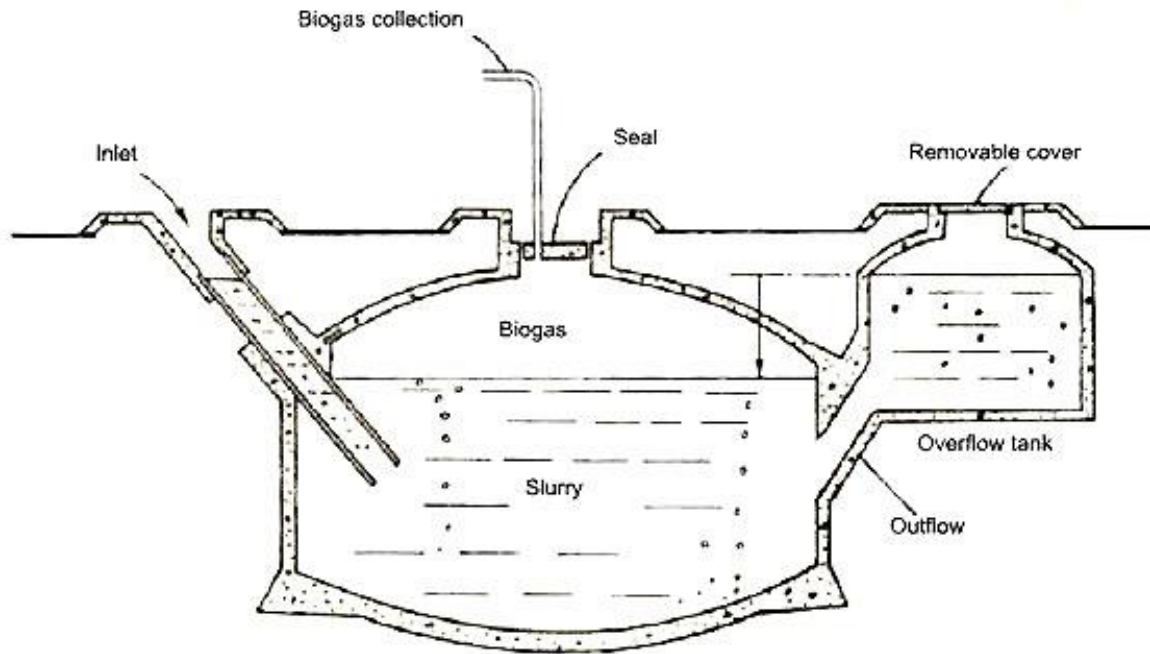- find out the gas leakages (if any)

Materials/Equipment:

- bio gas unit
- weighing scale (able to weigh up to 25kg)
- plastic bucket (to weigh the organic matter)

- solid organic matter
- water
- fresh cow dung
- burnt lime (CaCO$_3$)
- pH papers/pH meter
- suitable plastic bucket to collect sludge

Methodology/Procedure:

Identify the major components of a digester (Figures 4 and 5).
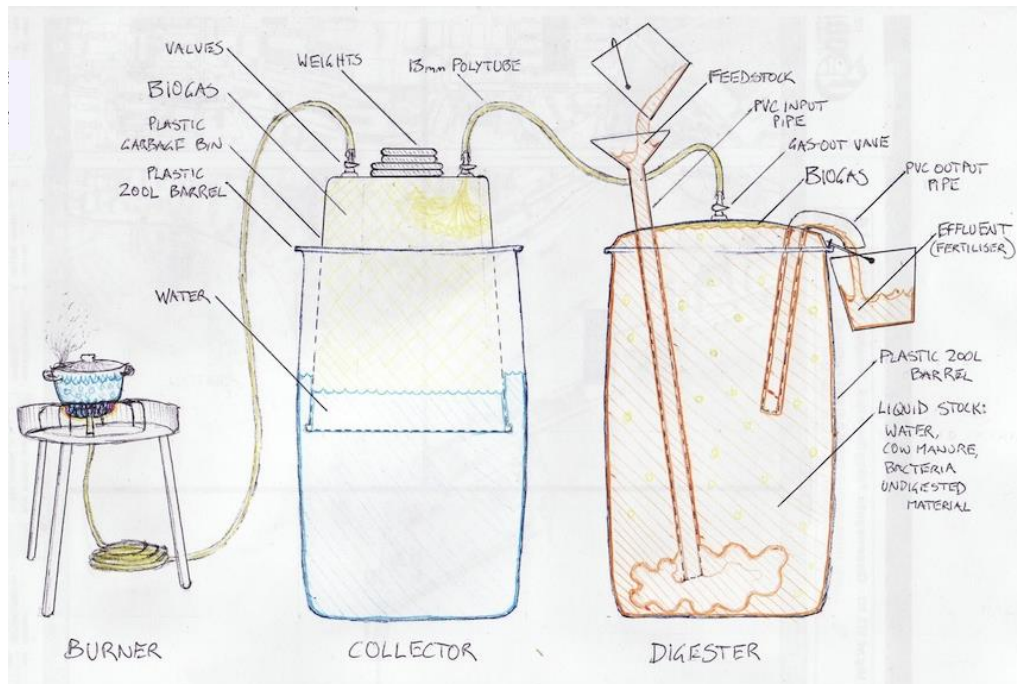
Figure 4a: A dome type Chinese digester

Figure 4b: Commercially available portable bio gas unit

If you do not have a portable bio gas unit, the following diagram (Figure 5) followed by Figures 6-8 will guide you to prepare your own bio gas unit using locally available materials.

Figure 5: Homemade bio gas unit

(Source: Shaun Hermans (2011))

The input pipe should be extended almost to the bottom area of the barrel to enter fresh feedstock at the bottom of the digester. The output pipe on the other hand should be set up to the upper area of the barrel, letting the existing liquid displace from the centre of the barrel into an effluent bucket when fresh feedstock enter the digester. Since solid particles of organic matter usually either float or sink, it would be mostly only liquid which comes out as effluent, leaving the larger particles in the digester to break down further. The collector can be prepared by cutting the top of a plastic barrel. It is then filled with water up to 3/4 of the volume and an inverted garbage bin is submerged (Figure 7). It is also essential to place a weight of either 5kg or 10kg on top of the biogas collector bin to apply some pressure to the biogas (a larger weight forces biogas out quicker).

The digester is now ready to be filled. For 200 L volume digester, about 20 kg of cow dung and sufficient water should be added to proliferate essential bacteria. This may take about a week. About 3-4 kg of kitchen waste with a similar volume of water can be added to the digester daily. Depending on the amount you would add to the digester, you can determine the size of your home digester.

The feeding materials should be selected carefully for the smooth running of your unit. Non/less biodegradable materials, coconut shells, flower stem of banana, materials with high lignin content, coconut residue etc. should not be added to the unit.

Figure 6a: External view of the digester

Figure 6b: the water level of the collector should be below the marked line

Figure 7: The collector is an inverted garbage bin submerged in water

Figure 8: The completed homemade bio gas unit

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Since pH in the system influences the efficiency of the bio gas process, precautions should be taken to keep the pH between 6.5 and 8. A suitable pH meter can be used to read the pH exactly or pH papers can also be used to get a rough pH value. Burnt lime can be added slowly to the system to increase the pH value.

In portable bio gas units, there is a discharge pipe at the bottom of the unit to discharge all the effluents with solid substances completely when necessary. But when emptying and cleaning the homemade system, careful removal of gas pipe is important.

Discussion:

Biogas is no more dangerous than other fuels. Bur certain precautions needed to be explained. Biogas can be explosive when mixed with air in the proportion of one part biogas to 8-20 parts air in an enclosed space. This situation may occur when a digester is opened for cleaning. Therefore, it is essential to avoid sparks, smoking, and open flames in closed circumstances or when opening a biogas digester for cleaning or repairing. A flashlight can be used to light inside the digester when necessary.

A biogas leak can be smelled if the hydrogen sulfide has not been removed from the biogas. If the rotten egg smell of biogas is noticed, care must be taken to enhance ventilation in order to get rid of the trapped gas before looking for the leak. Frequent smell checks for gas leaks in plastic pipes, Joints, clamps, and gate valves should be carried out.

In normal operations the pressure inside the system should always be greater. But, when the force created by the weight of the gases outside the biogas system is greater than the force inside the system, a negative pressure may arise. Negative pressure pulls air into the biogas system and the mixture of biogas and air might explode.

The benefits of bio gas when compared with other energy sources are diverse. The economic benefits of bio gas include treatment of solid waste without long term follow-up costs usually due to soil and water pollution, increased local distribution of fertilizer, chemical herbicides and pesticides demand, generation of income through compost and energy sales (biogas/electricity/heat) to the public grid, improved soil/agriculture productivity through long term effects on soil structure and fertility through compost use, reduction of landfill space and consequently land costs while environmental benefits include dramatic odour reduction, reduced pathogen levels, reduced greenhouse gas emissions and platform for reducing nutrient run-off. In addition, social and health effects associated with bio gas include creation of employment in bio gas sector, improvement of general conditions of farmers due to the local availability of soil improving fertilizer and decreased smell and scavenger rodents and birds.

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Workshop on Biosystems Technology held at University of Kelaniya from 20 to 27 June 2015