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A Review on Anaerobic Digestion

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Abstract

This paper aims to review the anaerobic digestion process of food waste because it is a promising approach for managing biodegradable organic waste materials and biogas is one of the alternative energy sources. Many factors govern and determine the efficiency of anaerobic digestion reactions and microbial metabolic functions. They are pH, temperature, environmental conditions, water content, C: N ratio, nutrient content of the food waste and natural inhibitors, etc. Hence, the above factors should be considered carefully in determining the required conditions for the anaerobic digestion process.

Key words: - Anaerobic digestion, Bio-gas, Food waste

1.1 Anaerobic Digestion

Anaerobic digestion is a biological degradation process by which complex organic material decomposes under the influence of microorganisms in the absence of oxygen. It is a well-established technology for stabilization and conversion of various organic wastes into bioenergy. The major end product is biogas, a mixture consisting mostly of methane and carbon dioxide. The anaerobic digestion includes four key stages namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. All of these steps are simulated by variety of anaerobic bacteria (Kalia, 2017).

1.1.1 Hydrolysis

The first step of the anaerobic digestion process is hydrolysis. The complex organic materials are broken down in to their constituent parts by hydrolytic enzymes in the hydrolysis phase. Several bacteria are involved such as *Clostridium Spp.* and *Eubacterium Spp.* The cellulose is broken down to sugar and alcohol by amylase, lipase and cellulase enzymes. The peptides and amino acids are results of protein break down by protease enzymes. The lipase enzymes are involved in the breakdown of lipids into fatty acids. Nucleic acid is broken down into purines and pyrimidines by nuclease enzymes (Karunarathna, 2012). It is a relatively slow step that can limit the rate of the overall digestion process, especially when solid waste substrates are used (Anukam et al., 2019).

1.1.2 Acidogenesis

It is the second and the fastest stage of the anaerobic digestion process (Chen, 2014). In this step, the products of the hydrolysis are subjected to the activities of acidogenic bacteria. Thus, final products of hydrolysis are converted to organic acids and carbon dioxide as given below. The principal organic acids produced during this stage are acetic acid, butyric acid, propionic acid, ethanol (Monnet, 2003).

Products of hydrolysis $\xrightarrow{\text{Nuclease Enzymes}}$ Propionate, butyrate, alcohol etc.

$C_6H_{12}O_6 \longleftrightarrow 2\ CH_3CH_2OH + 2\ CO_2$

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

$C_6H_{12}O_6 \longrightarrow 3\ CH_3COOH$ (Anukam et al., 2019)

1.1.3 Acetogenesis

In the acetogenesis process, simple organic acids are produced by bacteria such as *Syntrophobactor* and *Sytrophomonos*. Acetic acid, propionic acid, butyric acid and ethanol are some of results of the acetogenesis. The acetogenesis stage of anaerobic digestion is equally vital because it reflects the efficiency of biogas production since approximately 70% of CH_4 is formed through reduction of CH_3COO^-, which is the key intermediary product of the digestion process (Anukam et al., 2019).

Result of Acidogenesis $\xrightarrow{\text{Nuclease Enzymes}}$ Acetic acid + Propionic acid + Ethanol etc.

The reaction series associated with this stage are represented by the following equations.

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

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

$CH_3CH_2OH + 2\ H_2O \longleftrightarrow CH_3COO^- + 3\ H_2 + H^+$

(Anukam et al., 2019)

1.1.4 Methanogenesis

The final step of the anaerobic digestion process is methanogenesis in which the products of acetogenesis are converted to CH_4 and CO_2. *Methanocouse*, *Methanobacillus* and *Methano sarcinaere* bacteria are involved in this step. Initially, acetic acids are converted to methane and hydrogen carbonate. The acetolactic and methanogenic bacteria are responsible for this part of reaction. The second part is the hydrogen carbonate is converted to methane and it is done by methanogenic bacteria.

Acetic acid $\longrightarrow$ Methane + Carbon dioxide

Ethanol + Carbon dioxide $\longrightarrow$ Methane + Acetic acid

Carbon dioxide + Hydrogen $\longrightarrow$ Methane + Water

The reaction equation representing the condition taking place in the methanogenic stage is represented as follows.

$CH_3COOH \longrightarrow CH_4 + CO_2$

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

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

(Anukam et al., 2019)

1.2 Benefits of the Anaerobic Digestion

Anaerobic digestion has number of benefits. These benefits can be categorized as three groups namely environmental, economic, and energy benefits (https://mvseer.com/benefits-of-anaerobic-digestion/).

1.2.1 Environmental Benefits of the Anaerobic Digestion

1. Protect animal and human health by reducing pathogens
2. Value addition to waste and production of sanitized compost
3. Recycle nutrients on the farm, creating an economically and environmentally sustainable food production system
4. Less organic waste is sent to landfills thus protect the ground water and surface water
5. Carbon sequestration
6. Deactivate of weed seeds
7. Beneficial reuse of recycle water

1.2.2 Economic Benefits of the Anaerobic Digestion

1. Electricity and LP gas cost can be reduced
2. Minimum energy cost for process
3. Sludge and effluent can be used as fertilizer
4. Construction and operation of digesters creates local job opportunities and increases local tax revenue
5. Businesses specializing in nutrients, manure solids and energy markets
6. Development of Agro-tourism

1.2.3 Energy Benefits of the Anaerobic Digestion Processes

1. It is a net energy producing process
2. Biogas is one of the richest source of electricity, heat and transporting fuel

1.3 The Key Parameters that Influence the Digestion Process

1.3.1 pH Value

In a well-balanced anaerobic digestion process, almost all products of a metabolic stage are continuously converted into the next breaking down product without any significant accumulation of intermediary products such as different fatty acids which would cause a pH drop. A range of pH values suitable for anaerobic digestion has been reported by various researchers, but the optimal pH for methanogenesis has been found to be around 7.0. Similarly, found that a pH range of 6.8-7.2 was ideal for anaerobic digestion (Khalid et al., 2011). Although acceptable enzymatic activity of acid forming bacteria can occur at pH 5.0. Most anaerobic bacteria including methane-forming bacteria function in a pH range of 6.5 to 7.5, but optimally at a pH of 6.8 to 7.6 (Damásio, 2009). pH in an anaerobic digestion can be adjusted using several chemicals such as sodium bi-carbonate, potassium bi-carbonate, calcium carbonate (lime), calcium hydroxide (quick lime) and sodium nitrate. But, the chemicals that directly release bicarbonate alkalinity are preferred due to their desirable solubility, handling, and minimal adverse impacts (Damásio, 2009).

1.3.2 C/N Ratio

The composition of waste also determines the relative amounts of organic carbon and nitrogen present in the waste substrate (C/N ratio). A solid waste substrate with high C/N ratio is not suitable for bacterial growth due to deficiency of nitrogen. As a result the gas production rate and solids degradability will be low. On the other hand, if the C/N ratio is very low, the degradation process leads to ammonia accumulation which is toxic to the bacteria. It is found that a C/N within the range of 25-30 is considered to be optimum for an anaerobic digester (Damásio, 2009). The recommended C: N: P ratio for the anaerobic digestion is 100:5:0.5. Granule formation is the key factor in UASBR performance, and phosphate in the food waste is essential in forming granules (Ariyawansha et al., 2019).

1.3.3 Temperature

Temperature is one of the major important parameters in anaerobic digestion due its significant effects on the microbial community, kinetic process, stability, and methane yield. Lower temperatures during the process are known to decrease microbial growth, substrate utilization rates, and biogas production. In contrast, high temperatures lower biogas yield due to the production of volatile gases such as ammonia which suppresses methanogenic activities (Khalid et al., 2011). Anaerobic digestion commonly applies two optimal temperature ranges: mesophilic with optimum temperature around 35 °C and thermophilic temperature around 55 °C. Influence of temperature on the rate of anaerobic digestion process is shown in Figure 2.1 (Damásio, 2009).

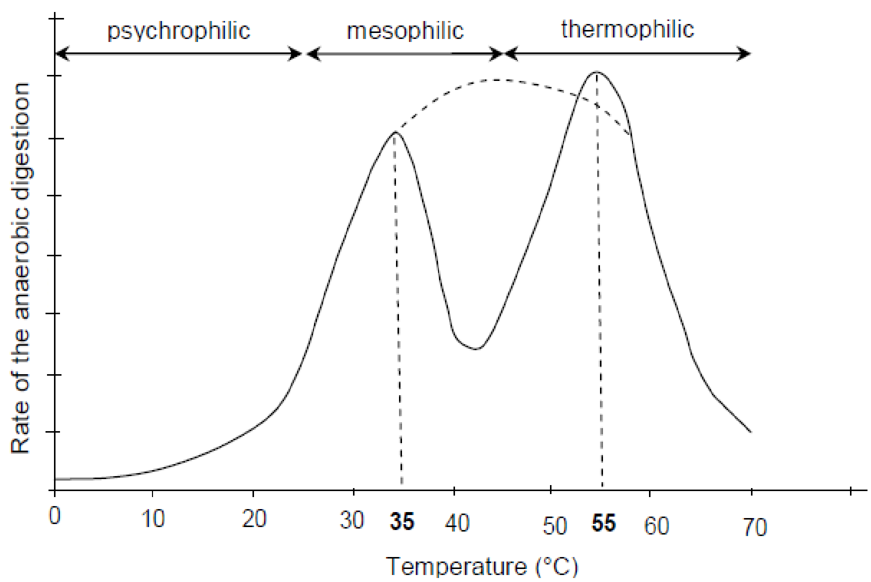

Figure 1 : Influence of temperature on the rate of anaerobic digestion process (Damásio, 2009)

1.3.4 Particle size

The particle size also has a significant role in anaerobic digestion of solid waste. During hydrolysis, smaller particle size provides a greater area for enzymatic attack. The increase of the average particle size in anaerobic digestion of food waste was reported to decrease the maximum substrate utilization rate coefficient reported that by reducing the size to 2 mm (Damásio, 2009).

1.3.5 Dilution

It is a key parameter in the successful operation to control the high performance of the reactor. The amount of water added to food waste can influence the performance of a digester significantly with respect to CH_4 generation and substrate degradation. Water or slurry can be added to dilute of the raw materials. Solid to liquid ratio changes with different systems. Average ratios are 10-25 % but some systems may change this range up to 30 % (Lou et al., 2012). It is done to reduce the concentration of inhibitory substances below the threshold in fed materials (Damásio, 2009).

1.3.6 Mixing

Proper mixing ensures that bacteria have rapid access to as many digestible surfaces as possible and that environmental characteristics are consistent throughout the digester. Recirculating water and biogas in the chamber to keep material moving has been used as a promising mixing method to enhance anaerobic digestion. However, excessive mixing can disrupt the microbes so slow mixing is preferred (Fajardo et al., 2016).

1.3.7 Hydraulic Retention Time

The hydraulic retention time (HRT) is a measure to describe the average time that a certain substrate resides in a digester. In a digester with continuous mixing, the contents of the reactor have a relative uniform retention time. If the HRT is shorter, the system will fail due to washout of the slowest growing microorganisms that are necessary for the anaerobic process consequently reduces the size of the digester, resulting in capital cost savings. Furthermore, a shorter HRT yields a higher biogas production rate, but less efficient degradation of organic matter. In some reports, it is found that the HRT of anaerobic digesters treating solid wastes varied from 3 to 55 days, depending on the type of waste, operational temperature, process stage(s) and configuration of the digesters. The HRT for dry anaerobic digestion ranges between 14 and 30 days and for wet anaerobic processes it can be as low as 3 days (Damásio, 2009). Specific biogas production with hydraulic retention time is illustrated in Figure 2.2 (Appels et al., 2008).

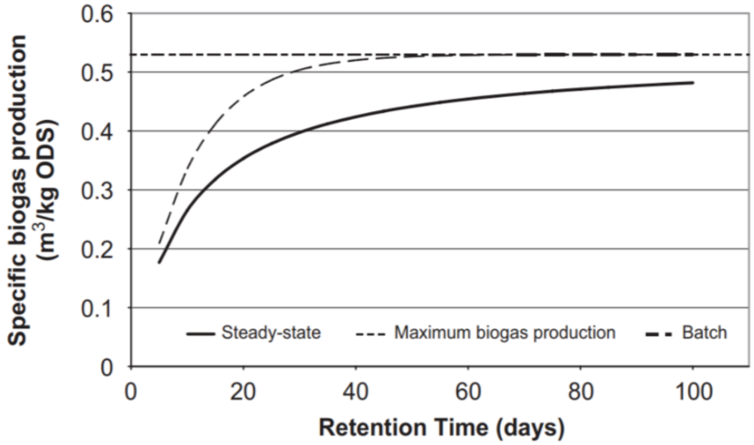

Figure 2 : Specific biogas production with hydraulic retention time (Lise Appels, 2008)

1.3.8 Organic Loading Rate

The organic loading rate (OLR) is defined as the amount of organic matter that must be treated by a certain volume of anaerobic digester in a certain period of time. The value of the OLR is mostly coupled with the HRT value. The potential danger of a rapid increase in the OLR would be that the hydrolysis and acidogenic bacteria would produce intermediary products rapidly. Since the multiplication time of methanogenic bacteria is slower, they would not be able to consume the fatty acids at the same rate. The accumulation of fatty acids will lead to a pH drop and hampering the activity methanogenic bacteria, causing a system failure (Damásio, 2009).

1.3.9 Toxicity

Inhibition in anaerobic digestion process by the presence of toxic substances can occur to varying degrees, causing upset of biogas production and organic removal or even digester failure. Several substances with inhibitory/toxic potential to anaerobic digestion, such as ammonia, sulfide, light metal ions, heavy metals and organic substances. These kinds of substances can be found as components of the feeding substrate or as byproducts of the metabolic activities of bacteria in the digester. Acclimation is the ability of microorganism to rearrange their metabolic resources to overcome the metabolic block produced by the inhibitory or toxic substances when the concentrations of these substances are slowly increased within the environment (Damásio, 2009).

1.4 Types of anaerobic reactor

1.4.1 Up-flow Anaerobic Sludge Blanket (UASB) Reactor

UASB reactor is considered as the most widely used high-rate anaerobic system for industrial and domestic wastewater treatment worldwide. The UASB processes are based on the development of dense granules (1-4mm) in the reactor (Nicolella, 2000). The anaerobic condition is facilitated during start up process. After that, continuous feeding is done, and continuously anaerobic digestion process occurs inside the reactor, while the wastewater flows upwards through a sludge blanket located in lower part of reactor, consequently biogas generates. And the sludge can be removed from the bottom part of the reactor. This sludge can be used as a fertilizer. The top of the reactor is used as biogas collection system with defined separation mechanisms that are incorporated in the basic design. It contributes the collection of biogas and also provides internal recycling of sludge by disengaging adherent biogas bubbles from raising the sludge particles. The mode of operating these reactors will determine the performance of the reactors (Hassan et al., 2013).

Some common issues were found during UASB reactor based research such as long start-up periods for the UASBRs is due to the time required for the anaerobic granulation (McHugh et al., 2003). Ion concentration increases due to decomposition of organic wastes under anaerobic conditions. As a result of that, inhibitory or toxic conditions occur and decreases gas generation rate (McHugh et al., 2003). A schematic diagram of an UASB reactor is shown in Figure 2.3.

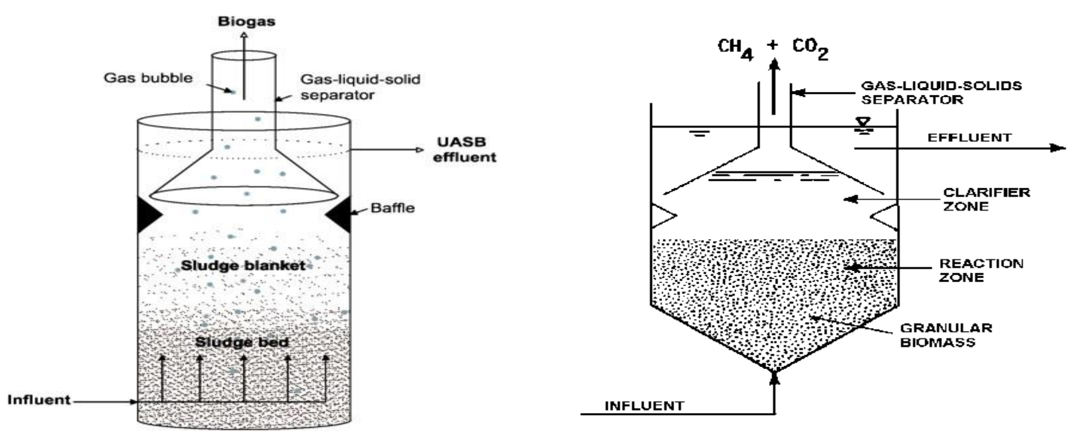

Figure 3 : A Schematic Diagram of an UASB reactor (Hassan et al., 2013)

1.4.2 Anaerobic Sequencing Batch Reactor

Anaerobic sequencing batch reactor (ASBR) process is a batch-fed, batch-decanted, suspended growth system and is operated in a cyclic sequence of four stages: feed, react, settle and decant as shown in Figure 2.4. Due to significant time is spent in settling the biomass from the treated wastewater, reactor volume requirement is higher compared to continuous flow processes. Nevertheless, it requires no additional biomass settling stage or solids recycle. No feed short-circuiting is another benefit of ASBRs over continuous flow systems. Operational cycle-times for the ASBR can be as short as 6 hours if the biomass granulation is achieved (Hassan et al., 2013). Normally this type of reactors is used in developing countries due to low construction cost and low maintenance cost.

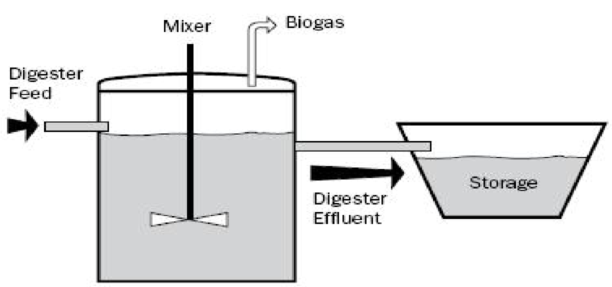

Figure 4 : A Schematic Diagram of an Anaerobic Sequencing Batch Reactor (Hassan et al., 2013)

1.4.3 Anaerobic Filter (Packed Bed)

Anaerobic filter is a fixed-film biological wastewater treatment process where fixed matrix provides an attachment surface that supports the anaerobic microorganisms in the form of a biofilm. As wastewater flows upwards through this bed and dissolved pollutants are absorbed by biofilm and thus, the treatment occurs. Anaerobic filters were the first anaerobic systems that eliminated the need for recycle and solids separation while providing a high SRT/HRT ratio. This leads eventually to short circuiting and channelling flow, and anaerobic filters are therefore unsuitable for wastewaters with high solids contents (Hassan et al., 2013). Additionally, there is a relatively high cost due to the packing materials.

1.4.4 The Expanded Granular Sludge Bed Reactor (EGSB)

The expanded granular sludge blanket reactor is functioning with high velocity. And it has high loading rate than the UASB reactor. It can be introduced as a modification of the conventional UASB reactor. The up-flow velocity of the reactor is comparatively high (>4 m h^{-1}). The performance of reactor can be high at low temperatures (Seghezzo, 1997).

1.4.5 Anaerobic Baffled Reactor (ABR)

ABRs are widely used in wastewater treatment plant to remove heavy sediment solids with the intention that the carryover wastewater will have lower COD level before going to next step of processes. Owing to the nature of wastewater under anaerobic conditions, granulated sludge blanket is formed. As the wastewater flows up throughout the sludge granules, the solids are trapped in the sludge blanket where anaerobic bacteria consume the organics as their food. A typical construction of the tank or reactor usually comprises of different compartments with various outlet levels and having a series of arranged baffles. ABR with several compartments that is designed to reduce the suspended and organic matter in the wastewater is shown in Figure 2.5. Raw wastewater enters the ABR tank through the inlet tubes, which directs the flow to the bottom of the first compartment (Hassan et al., 2013).

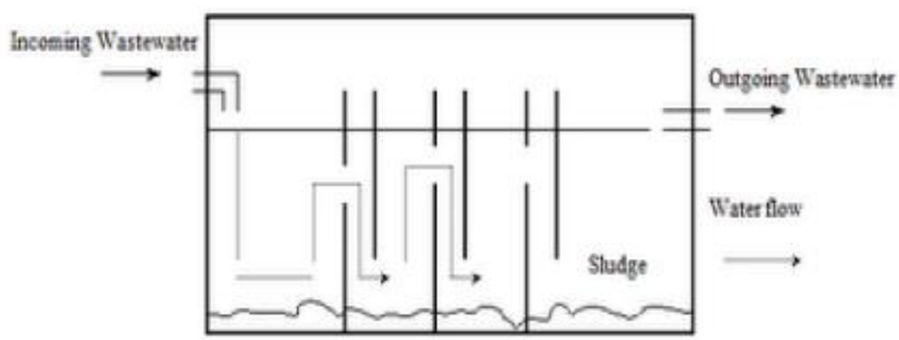

Figure 5: A Schematic Diagram of an Anaerobic Baffled Reactor (Hassan et al., 2013)

1.4.6 The Internal Circulation Reactor (ICR)

The sludge bed is found in the bottom of the reactor. Gas-liquid separator located at top of the reactor. The biogas generates at the bottom of the reactor and the gas transports upwards together with waste. The second stage is located in the upper part of the reactor, allows sedimentation of the organic material and reduces the possible wash out. Small amount of the gas produced in that part too. The IC reactor is a device that combines the principle of the UASB and UGSM (Pereboom JHF et al., 1994) .

1.4.7 Continuously Stirred Tank Reactor (CTR)

Back mix reactor is another name for continually stirred tank reactor. Gas mixing mechanism is operated inside the reactor. It is assumed that concentration of microorganisms is uniform throughout the reactor (Fantozzi & Buratti, 2009).

1.4.8 Fluidized Bed Reactor (FBR)

FBR is a biological reactor that accumulates a maximum active attached biomass thus handling fine suspended solids without blocking by minimizing the volume occupied by the media and maximizing the surface area available for microbial attachment. A maximum specific activity of attached biomass may be achieved for a given reactor volume. A filter containing extremely small particles (0.5 mm) provides sufficient surface area to achieve these benefits. To attain fluidization of the biomass particles, units must be operated in an up-flow mode. Rate of liquid flow and the resulting degree of bed expansion determines whether the reactor is termed expanded bed or fluidized bed system (Hassan et al., 2013).

1.5 Biogas

1.5.1 History of biogas

Biogas was used for heating bath water in Assyria long ago in the 10th century B.C. However, well documented attempts to harness the anaerobic digestion of biomass by humans date from the mid nineteenth century. In the 1890s, digesters were constructed in New Zealand and India, with a sewage sludge digester, and in UK as fuel street lamps. In Guangdong Province, China, commercial use of biogas has been attributed to Guorui Luo who constructed an $8m^3$ biogas tank fed with household waste and later they founded a company to popularize this technology. The first German sewage treatment plant to feed biogas into the public gas supply began to do so in 1920, while in the same country the first large agricultural biogas plant began operating in 1950. The spread of biogas technology gained momentum in the 1970s, when high oil prices motivated research into alternative energy sources. The fastest growth of biogas use in many Asian, Latin American and African countries was in the 1970s and the first half of the 1980s. During that period the Chinese government promoted "biogas use in every rural family" and facilitated the installation of more than seven million digesters. From the second half of the 1980s, while biogas technology found more applications in industrial and urban waste treatment and energy conservation, its dispersion into rural areas slowed. In China, the end of 1988, only 4.7 million household biogas digesters were reported particularly since the turn of this century there has been another rapid increase in the number of plants and in 2007 there were 26.5 million biogas plants the overwhelming majority household systems with volumes from 6 to 10 m^3. Meanwhile, in 1999 there were over three million family-sized biogas plants in India and by the end of 2007, the Indian government had provided subsidy for the construction of nearly four million family-sized biogas plants. The National Project on Biogas Development (NPBD) has run since 1981–1982 and promotes its own digester designs while providing financial support and various training and development programs (Bond et al., 2017).

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1.5.2 Composition of biogas

Biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2) with small amounts of hydrogen (H_2), nitrogen (N_2), hydrogen sulfide (H_2S), oxygen (O_2), water (H_2O) and saturated hydrocarbons (i.e. ethane, propane). The removal of the water and the toxic hydrogen sulfide is important in order to avoid detrimental effects. Biogas has composition that has to be taken into account during its use in spark ignition engines as the control system used is only for a single composition fuel. The detailed chemical composition of biogas is illustrated in Table 2.1, general features of the biogas are given in Table 2.2 and the biogas formation steps are shown in Figure 2.6.

Table 1: The chemical composition of the biogas (Bharathiraja et al., 2018)

Constituent	Formula	Concentration % (v/v)
Methane	CH_4	40-75
Carbon dioxide	CO_2	15-60
Moisture	H_2O	1-5
Nitrogen	N_2	Traces
Hydrogen Sulphide	H_2S	0-5000 ppm
Oxygen	O_2	< 2 %
Trace gases		< 2 %
Ammonia		0-500 ppm

Table 2: General features of biogas (Riuji, 2009)

Energy content	6.0 - 6.5 kW/m^3
Fuel equivalent	0.60-0.65 L oil/m^3 biogas
Explosion limits	6-12 % biogas in air
Ignition Temperature	650-750 ^oC
Theoretical air demand	5.7m^3 air/m^3 burning gas
Critical pressure	75-89 bar
Critical temperature	-82.5 ^oC
Normal density	1.2 kg/m^3
Molar mass	16.043 g/mol
Smell	Bad eggs

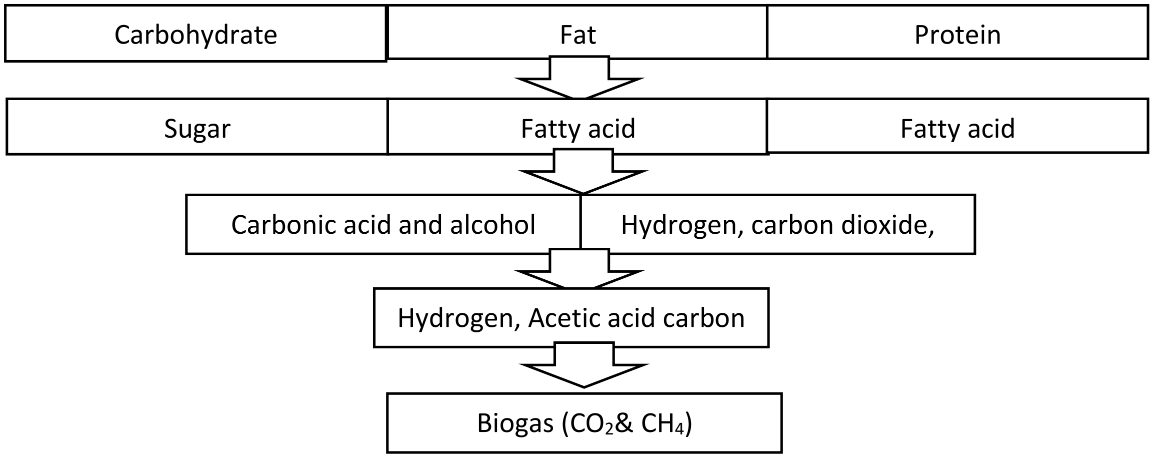

Figure 6: Biogas formation under anaerobic digestion process

1.5.3 Application of biogas

The (thermal) energy available from the methane contained in biogas is about 6 to 8 kWh/m^3. This corresponds to half a liter of diesel oil and 5.5 kg of firewood. In addition, the biological energy pit concept, involves the discharge of all of the discharges of domestic wastewater, domestic wastes (foods and vegetables) and toilet waste into a single pit. A separate toilet is not required. This allows for methane combustion of biogas and organic liquid fertilizers, and refining by filtration units provides the necessary water for the plantation needs. Gas demand can be defined on the basis of energy previously consumed. 1 kg of human faces generates about 50 liters of biogas, 1 kg of cattle dung delivers 40 liters of biogas, and 1 kg of chicken droppings generates about 70 liters of biogas (NWP, 2006). Gas consumption for cooking per person and per meal is between 150 and 300 L biogas. Approximately 30-40 L biogas is required to cook one liter of water, 120-140 L for 0.5 kg rice and 160-190 L for 0.5 kg vegetables. Tests in Nepal and Tanzania have shown that the consumption rate of a household biogas stove is about 300-400 L/h. However, this depends on the stove design and the methane content of the biogas. The following consumption rates in liters per hour (L/h) can be assumed for the use of biogas:

household burners: 200-450 L/h

industrial burners: 1000-3000 L/h

refrigerator (100 L) depending on outside temperature: 30-75 L/h

gas lamp, equivalent to a 60 W bulb: 120-150 L/h

biogas/diesel engine per bhp: 420 L/h

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