Bio-methane Generation from Organic Waste: A Review

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***Abstract*— Anaerobic digestion of organic waste can address both energy recovery and pollution control. A variety of agricultural, industrial and domestic wastes can be anaerobically digested as they contain easily biodegradable material. Biogas contains 50 -70% methane and 30-50% carbon dioxide as well as small a amounts of other gases with calorific value of about 21-24 MJ/m³. This paper reviews the history of biogas, biogas production stages and operating parameters. The anaerobic digestion configuration and potential substrates for biogas production are also considered.**

***Index Terms*—Anaerobic digestion, biodegradable, energy, substrates, waste**

I. Introduction

THE exhaustion of fossil fuels and the global warming situation are strong motivating factors for alternatives fuels research [1]. Many countries are interested in sustainable renewable energy sources such as; geothermal power, wind power, small-scale hydropower, solar energy, biomass energy, tidal power, and wave power [1]. Biomass energy is environmental friendly and requires less production energy, Zheng et al., (2012) [2]. Various biomasses derived from the carbonaceous waste of human, animals and natural resources could be utilised as renewable energy resources [3]. Solutions to waste problems such as food waste and manure including gasification, pyrolysis and plasma technologies (incineration) of solid wastes have been developed [4]. These technologies involve the combustion of organic waste at elevated temperatures in the absence of oxygen [5]. These technologies require a lot of energy to operate, and some facilities consume more energy than what they can produce [4]. Anaerobic Digestion (AD) of organic matter could be a better option. Microorganisms transform biodegradable substrates into biogas and stabilized solid residues [6]. The general anaerobic transformation is described as in (1), Tchobanoglous et al, 1993, [7].

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$$\text{Organic matter} + H_2O + \text{nutrients} \longrightarrow \text{new cells} + \text{resistant organic matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{Heat} \quad (1)$$

Biogas was used for heating bath water in Assyria in the 10th century B.C. and in Persia during the 16th Century [8]. The first digestion plant was built in Bombay, India in 1859 [9]. In England, AD was realized in 1895 when biogas was recovered from a "carefully designed" sewage treatment facility and was used to fuel streets lights in Exeter [8]. Today, millions of micro AD systems exist in developing countries, particularly China, India and Nepal while developed countries like Germany, Austria, Denmark and Scandinavian tend towards large industrial scale plants [10], Fig. 1. In Germany, biogas technology is advanced and is being used to produce green electricity in the Mega Watt range [11].

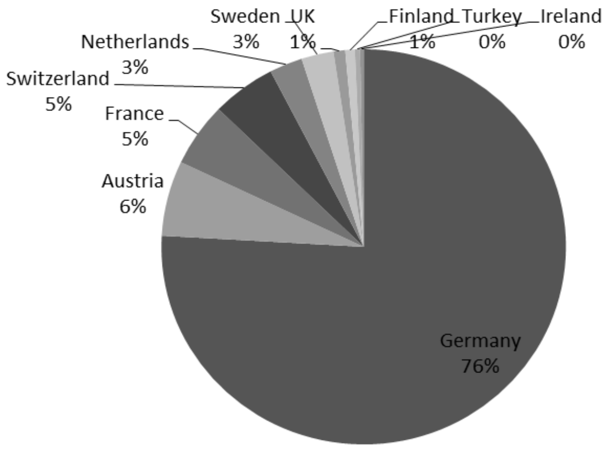

Fig. 1. Countries with the most AD [12]

AD technology and plants have improved over the years. Fig. 2 shows the number of biogas plants built in Germany between 1991 and 2006. Although AD was first built in 1859, it gained attention in the 1970's as a means of stabilizing Municipal Solid Waste (MSW) and also as a renewable energy source [13].

Biogas is approximately 60% methane and 39 % Carbon dioxide with small amount of water vapour, hydrogen, sulphide and ammonia, Table I. It can be used as raw to generate heat or electricity or enriched into bio-methane (> 99% methane) [8]. Bio-methane can be used as vehicular fuel. Co-digestion has been found to improve the digestion process [15], [16]. AD process can be divided into 4 phases which are hydrolysis, acidogenesis, acetogenesis and methanogenesis [17].

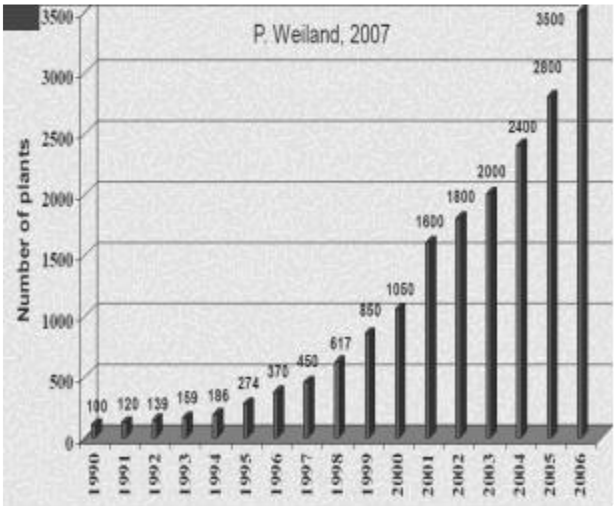

Fig. 2. Development of biogas industry in Germany [14]

TABLE 1
BIOGAS COMPOSITION [15]

Component	Dimension	Content
CH_4	%	50 to 80
CO_2	%	15 to 45
H_2S	mg/m^3	0 to 5000
NH_3	mg/m^3	0 to 450
Humidity	-	Saturated
Calorific Value	MJ/m^3	20 to 25
Calorific Value	kWh/m^3	5.5 to 8

II. Biogas Production

A. Hydrolysis

Hydrolysis is the first stage of the organic waste decomposition process involving the breakdown of large organic polymer chains into smaller molecules such as simple sugars, amino acids and fatty acids [17]. Other products such as hydrogen and acetate maybe used by methanogens later in the process [18]. Saccharolytic and proteolytic microorganisms break down sugars and proteins respectively [17]. The various enzymes for sugars and fats are shown in Table II, Anna & Asa (2010) [17].

TABLE II
HYDROLYTIC ENZYMES AND THEIR FUNCTIONS [17]

Enzyme	Substrate	Break down Products
Proteinase	Protein	Amino Acids
Cellulase	Cellulose	Cellobiose and glucose
Hemicellulase	Heicellulose	Sugars e.g. glucose, xylose, mannose
Amylase	Starch	Glucose
Lipase	Fats	Fatty acids and glycerol
Pectinanse	Pectin	Sugars e.g. galactose, arabinose

B. Acidogenesis

Fermentative bacteria (acidogenic) produce an acidic environment in the digestion tank while creating ammonia (NH_3), Hydrogen (H_2), Carbon dioxide (CO_2), Hydrogen sulphide (H_2S), shorter volatile fatty acids, organic acid (acetic, propionic acid, butyric acid, succinic acid, lactic acid etc.) as well as low alcohols [18]. However the resulting organic matter is still very large and unsuitable for methane production.

C. Acetogenesis

During this step, acetogens, produce acetic acid, carbon and energy sources. Close cooperation is required between oxidative organisms and methane producing organisms that are active during methanogenesis [17]. This process consumes hydrogen gas, thus keeping its concentration at very low levels.

D. Methanogenesis

The final stage of AD methane production stage, where methanogens produce methane from hydrogen, carbon dioxide and acetate as well intermediates products from hydrolysis and acidogenesis [17]. Methanogenesis constitutes the final stage of AD in which methanogens create methane from the final products of acetogenesis (i.e. hydrogen gas, carbon dioxide and acetate) as well as from some of the intermediate products from hydrolysis and acidogenesis [19]. In this stage methane and carbon dioxide are formed by various methanogens [17]. Various microorganisms are active during this stage. Methanogens are not common bacteria but are called archaea [20] and can easily be distinguished from common bacteria using microscopes. Methanogens are sensitive to pH changes and presence of heavy metals and organic pollutants. The pathways for acetic acid and carbon dioxide in the production of methane are shown in (2) and (3).

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

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (3)$$

The main pathway for methane production during methanogenesis is the conversion of acetic acid as in (3) [17] and is summarized in Fig. 3.

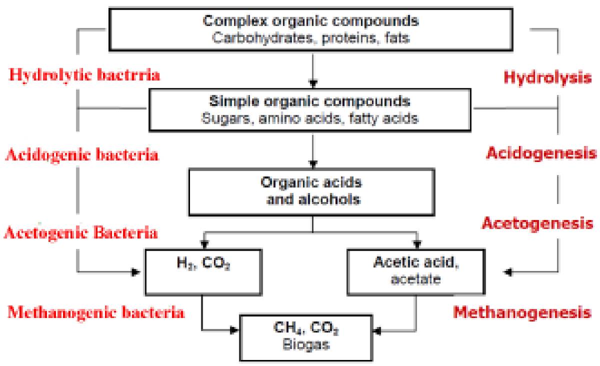

Fig. 3. Anaerobic digestion process [17]

III. AD Operating Parameters

A. Temperature

The optimum temperature depends on the microorganisms which are categorized as psychrophilic, mesophilic and thermophilic [17 as well as the environment of origin. The optimum temperatures for psychrophilic, mesophilic and thermophilic microorganisms are 10ºC, 20-45ºC and > 50ºC respectively, Fig 4 [17]. At less than 10ºC, the anaerobic process takes 3 times more than the normal mesophilic time process [21]. Reference [21] reported 200 – 300 L of methane production per day from 1000L digester using psychrophilic organisms. This was about 20 to 30% of the output of digesters in warmer climates. Thermophilic digestion systems are considered to be less stable and high energy consumption but produce a lot of biogas.

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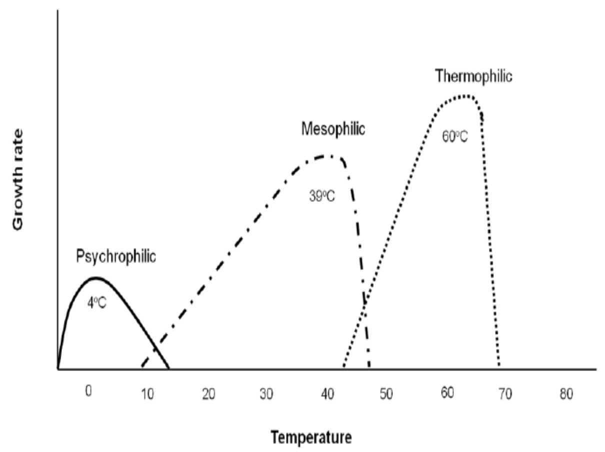

Fig. 5. Growth of microorganisms at different temperatures [17]

B. pH

In anaerobic digestion, pH control is important to ensure the health of the methanogens [18]. Methanogens prefer a pH environment between 7 and 7.5 [17] although there are several biogas plants operating at pH of 8 in Sweden [22]. During the acidogenesis, pH is lowered by the acid production, hence continuous monitoring and adjustment is required.

C. Retention Time

Retention time varies with substrate composition, digestion system configuration and processes and as well as temperature. Sugar and starch rich substrates can easily be digested [17] for example industrial waste water which contains soluble organic matter. In this case hydrolysis is not required resulting in shorter retention times. Longer retention times are required for the fibre and cellulose plant matter with hydrolysis limiting the decomposition process. For example, in Germany retention times of up to 50-100 days are common to ensure stable operation and satisfactory digestion of energy crops [23]. For thermophilic digestion, residence times are about 14 days [12]. In two stage mesophilic digestion, residence times vary from 15 to 40 days [12]. Retention time usually referred to as hydraulic retention (HRT) is usually between 10 and 25 days. Sometimes the retention time of the particulate material, or solids retention time (SRT) of the process is specified. In most situations, HRT and SRT are equal with the exception of digestion tanks where part of the residues are returned into the process, then SRT becomes longer than HRT. This is practised during digestion of industrial sewage where the feed has a higher water content. Then the recirculation of digested, thickened sludge, including biomass, allows a longer retention times for the decomposition of incoming organic matter. In colder climatic conditions, the HRT maybe as high as100 days as compared to 30-50 days for warmer climates. Shorter retention times risk bacterial washout while larger digesters are required for longer retention times.

D. Degree of Digestion

Higher retention may increase the contact time between microorganisms and substrates [17]. Generally, batch processes have a higher degree of digestion than continuous ones. In a batch process, the degree of digestion can theoretically be 100%. Readily biodegradable substrates, such as liquids from pressed sugar beets, can have degrees of digestion of more than 90% while about 60% has been reported for high fibre crops [24]. Generally, the lower the degree of digestion in the actual digestion tank, the greater is the potential for methane production in the post-storage stage [17].

E. Loading Rate

To determine the loading correctly, it important to know the dry solid and volatile contents of substrates. Reference [25] reported an increase in methane production with reduction in loading rate. This is because if the loading rate is too high there will be more substrate than what the bacteria can decompose. Excess substrate at the beginning of the process, leads to the build-up of undecomposed material such as fatty acids. This reduces the pH and creates an inbalance in the entire decomposition chain [17].

F. Mixing

Mixing promotes contact between microorganisms, substrate and nutrients as well as uniform temperature distribution. Gentle mixing leads to the formation of aggregates and prevent methane producing organisms from being washed out by the liquid. Mixing also reduces sedimentation and hence reduces the risk of foaming.

G. C. N Ration

The optimum C: N ratio for microbes is 20-30:1, Bardiya and Gaur, 1997 [26]. Methanogens utilizes nitrogen for their protein requirements. For higher C: N ratios, nitrogen depletion will result in reduced biogas production. Higher ratios will result in excess nitrogen leading to the formation of ammonia. This increases pH level beyond 8.5 which then inhibits the activity of microbes and consequently gas production [27].

H. Particle Size

According to EU Regulation EC 208/2006, the maximum particle size for adequate digestion is 12 mm. Reference [17] also showed a correlation between particle size and methane production. On the other hand, too small particles can clog the digestion systems.

IV. AD CONFIGURATION

Digesters can either be batch or continuous depending on the substrate being treated. Batch systems are simple, cheaper and requires less equipment [18]. Continuous digestion allows for constant gas production. A single (one step digestion) or multiple digesters may be used. For one-step digestion, all stages in the microbial breakdown process, i.e. hydrolysis, fermentation, anaerobic oxidation and methane production take place simultaneously particularly for completely mixed processes. It is mainly applicable for the treatment of sludge, food waste and manure. In some cases, process liquid is returned to the system and this increases retention time and allows more microbes to remain in the process [28]. In a two – stage digestion, the first step involves loading material into a digestion tank where hydrolysis, acetogenesis and

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acidogenesis occur. It is then introduced into the methanogenic reactor for methane production. The two-stage process results in fast and efficient formation of biogas in the second stage with methane concentrations of up to 85% [29].

V. Substrates

A. Introduction

Waste must be putrescible (digestible) for it to be used or biogas production. Currently in Sweden, the main source of waste for biogas production is municipal waste treatment plants [17]. At Swedish co-digestion plants biogas production sources are slaughter house waste (65%), food waste (25%), manure (10%) and other (5%). For co-digestion plants, sources include food waste and manure. Total biogas production today is equivalent to an energy output of about 1.3 TWh/year. However the theoretical potential energy production from domestic waste excluding forest waste is estimated to be around 15TWh / year [22]. The potential of sewage and manure for AD is limited because as much of the energy is taken by the animals which produce the waste, hence the need for co-digestion. For example biogas production from dairy manure maybe enhanced by co-digestion with grass, corn, slaughterhouse waste, restaurant oils, grease and fats as well as organic household waste [12].

B. Choice of Substrate

The decomposition of materials is governed by process parameters such as load, temperature and retention time as well as pre-treatment [18]. Substrates must meet nutritional requirements of microorganisms for energy, new cells formation and as well trace elements and vitamins for microbial enzymes. The C: N ratio should not be too high to avoid nitrogen deficiency [30]. The optimum C: N ratio is also influenced by levels of phosphorus and trace elements [31], process decomposition efficiency and substrate composition [32]. Not too high levels of C: N ratios can stimulate methanogenesis. The C: N ratios for various substrates is shown in Table III. Materials have different energy content, hence produce gas with varying methane content [17]. Table IV shows approximate biogas volumes and methane content from carbohydrates, protein and fats. These values can be used for theoretical calculation of the amount of gas that can be produced.

Proteins are a rich energy sources and produce a lot of methane during material decomposition. Examples of such waste include slaughterhouse waste, swine and chicken manure and stillage from the ethanol industry. Proteins are first converted into amino acids during hydrolysis and these are later converted to ammonia and ammonium. An increase in ammonium production due to increase in temperature and pH leads to foaming [38]. Materials with high sugar content should be mixed with less digestible material to achieve a balanced process [39]. Chemical pre-treatment, which breaks down the crystalline structure of cellulose, can increase the rate of degradation and produce higher biogas yields [31], [33], [40]. Although fats are very energy rich materials which can produce a lot of biogas they also cause process instability [41] due to foaming at high temperatures.

TABLE III
C/N RATIO OF MATERIALS USED AS SUBSTRATES FOR BIOGAS PRODUCTION [30]

Material	C/N ratio
Cattle manure-liquid	6 to 20
Chicken manure	3 to 10
Swine manure-liquid	5
Straw	50 to 150
Grass	12 to 26
Potatoes	35 to 60
Sugar beet/beet foliage	35 to 46
Cereals	16 to 40
Fruits and vegetable	7 to 35
Mixed food waste	15 to 32
Food waste	3 to 17
Slaughterhouse waste –guts	22 to 37

TABLE IV
THEORETICAL BIOGAS COMPOSITION FROMCARBOHYDRATE, FAT AND PROTEIN [34]

	Biogas formed (m^3/kg VS)	Biogas composition: CH4: CO2 (%)
Carbohydrates	0.38	50:50
Fats	1	70:30
Protein	0.53	60:40

C. Moisture Content

Wetter materials are prefer for easier handling with standard pumps instead of energy – intensive concrete pumps or physical movement [12]. Also wetter materials occupy a lot of volume relative to the gas produced. Bulking agents such as compost maybe added to dilute solutions to increase the solid content of feed material.

D. Co-digestion

Co-digestion improves biogas production because complex material is likely to have most of the components required for microbial growth [35], [36]. It also reduces the amount of solid waste generated.

E. Pre-treatment

Pre-treatment is done to destroy pathogenic microorganisms, remove unbiodegradable material, concentrate organic material content and feed preparation [37]. Mechanical pre-treatment maybe achieved using mills, blenders, screws and rotating knives. Thermal, chemical or biological means maybe used to achieve pre-treatment [37]. Methane production was reported to increase with reduction in particle size [17].

F. Potential Substrates

Potential substrates include food waste, manure, crop residue, slaughterhouse waste as well as stillage and other sulphur containing material. Stillage waste is rich in protein and can possibly lead to ammonia inhibition. Thus stillage should be co-digested with with more carbohydrate rich material. Food waste is a good feed source for biogas

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production as it contains proteins, fats, carbohydrates and various trace elements, this promote a balanced process [40]. Food waste must not contain a lot proteins as this will lead to ammonia inhibition [42]. Pigs and chicken manure contain more protein compared to cattle manure. This is because most of the organic material in the feed has already been converted into methane in the stomach of ruminants. Various crops and plant materials such as corn, grain, sugar beets, potatoes, fruit, grass maybe used for biogas production [43]. Many bioenergy crops have a high C: N ratio and mixing with more nitrogen-rich material can achieve optimum process conditions. Co-digestion of energy crops with manure can increase methane recovery by 16-65% [43]. Slaughterhouse waste has high protein and fats contents, thus very energy rich hence high biogas production potential. Stable process operation can be achieved with co-digestion [44]. Fig. 6 shows biogas yield from various substrates [15].

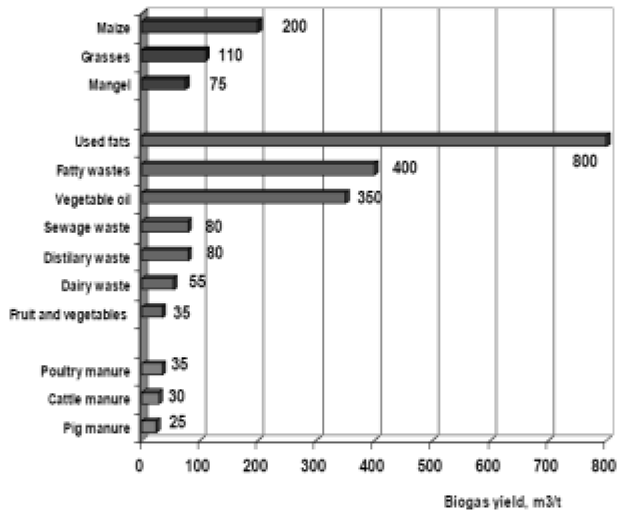

Fig. 6. Biogas yield from various biomass [15]

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