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A review on production of biogas, fundamentals, applications & its recent enhancing techniques

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ABSTRACT

Biogas, a clean and renewable form of energy could very well substitute (especially in the rural sector) for conventional sources of energy (fossil fuels, oil, etc.) which are causing ecological–environmental problems and at the same time depleting at a faster rate. Despite its numerous advantages, the potential of biogas technology could not be fully harnessed or tapped as certain constraints are also associated with it. Most common among these are: the large hydraulic retention time of 30–50 days, low gas production in winter, etc. Therefore, efforts are needed to remove its various limitations so as to popularize this technology in the rural areas. Researchers have tried different techniques to enhance gas production. This paper reviews the various techniques, which could be used to enhance the gas production rate from solid substrates.

Introduction

The use of renewable for bio energy production is in discussion because of the concurrence to the food or animal feed. The treatment of organic waste is necessary in order to keep clean the environment. The combination of those proposals, the waste utilization and the production of renewable energy can be combined with several techniques. Anaerobic digestion (AD) is the conversion of organic material directly to gas, termed biogas, a mixture of mainly methane (CH4) and carbon dioxide (CO2) with small quantities of other gases such as hydrogen sulphide (H2S), ammonia (NH4), water vapor, hydrogen (H2), nitrogen (N2) etc. AD is the process of decomposition of organic matter by a microbial consortium in an oxygen-free environment. It is a process found in many naturally occurring anoxic environments including watercourses, sediments, water logged soils and the mammalian gut. Biogas is one of the most efficient and effective options among the various other alternative sources of renewable energy currently available. It is produced through anaerobic digestion processes where the microorganisms convert complex organic matter into a mixture of methane and carbon dioxide. The anaerobic digestion of biomass requires less 2 capital investment per unit production cost compared to other renewable energy sources, such as hydro, solar and wind energy [1]. It has been early demonstrated that biogas production from crop residues is economically feasible on a farm-scale level (50–500 kW) [2].

Biogas and its utilization

Biogas is a mixture containing predominantly methane (50-65% by volume) and carbon dioxide and in a natural setting it is formed in swamps and anaerobic sediments, etc., due to its high methane concentration, biogas is a valuable fuel. Wet (40-95%) organic materials with low lignin and cellulose content are generally suitable for anaerobic digestion Figure 2.

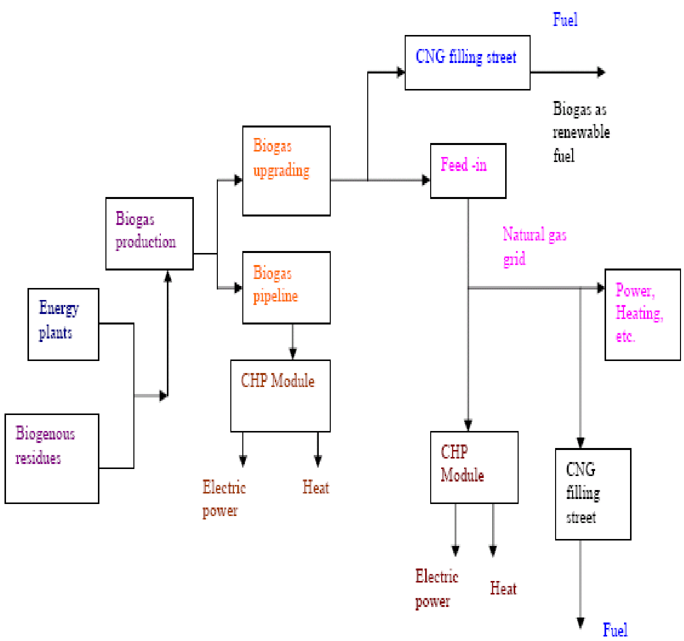

Figure 2 Over view of biogas utilization pathways

Utilization of fermentation residue

There are different utilization options for the fermentation residues from agricultural as well as waste material biogas plants. The quality of fermentation residue depend on the input substrate, process operation and degradation rate. Especially in agricultural plants it is common to use fermentation residues without a previous mechanical drainage. The fermentation residue is directly spread on agricultural areas as fertilizer during the vegetation period. By that the nutrient and carbon cycle can largely be closed. To be able to spread the fermentation residues an adequate amount of agricultural areas is required. If there are

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not enough agricultural areas the fermentation residue will be given to a manure market or is drained for further transport. The fermentation residue is given to a part or full treatment. During part treatment only a share of nutrients and carbon compounds is separated by draining. The objective of full treatment is to process the fermentation residues in a way that nutrients are available in high concentrations and that the purified waste water can be given to a waste water treatment plant, which is also called indirect discharge or direct discharge if given to receiving water after treatment. The treated clear water can furthermore be used as process liquid for fermentation. Figure 3 illustrates the general possibilities of treatment and utilization of fermentation residues.

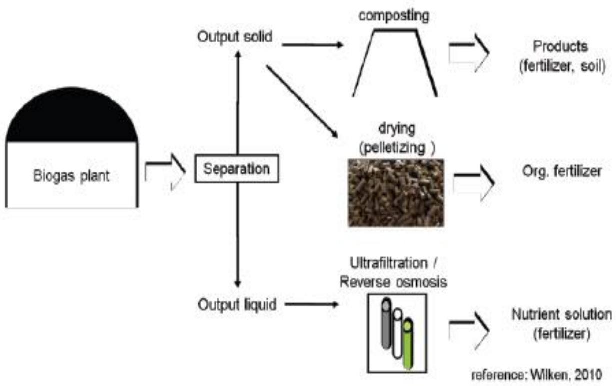

Figure 3 Treatment options of fermentation residues

Emissions

There are many discussions in literature on the amount of diffuse greenhouse relevant emissions produced by biogas plants. Recent studies show a very diverse view on that (e.g. Cuhls et al. (2009)[3]. The parameters are TOC mass concentration (kg/m³) and mass flow for TOC (kg/h) and mass flow limit for ammonia (kg/h). Organic carbon emissions (especially methane) develop under certain conditions e.g. during delivery of substrates; as odour emissions; as ammonia in the sewage storage; as methane in seepage water; as methane slip during gas treatment; as formaldehyde and methane in emissions from combined heat and power units; during stand still, maintenance and reparation of biogas plant; as odour, ammonia, methane and laughing gas during storage and spreading of fermentation residues [4]. Cuhls et al. (2009)[3] have primarily examined their measurements with compost plants as well as with a few fermentation plants with downstream composting. Up to now it was agreed that the methane slip from biogas plants is about 3%. This value is considered for the climate balance of fermentation plants.

Fermentation

Depending on how the fermentation substrates will be fed into the fermenter, also called fermenting tank, we speak about:

- continuous or
- discontinuous processes.

In the case of discontinuous (batch) processes the fermenter is filled with fresh substrate and hermetically closed. Discontinuous processes are, as a rule, operated as dry fermentation (also called solid fermentation). Here, the garage-like fermenters are simply filled and emptied by means of wheeled loaders. The gas production starts slowly after filling and declines again slowly after reaching the maximum. Here, the substrate remains in the tank without adding or taking off substrate. After the biogas production will have been completed the fermented substrate will be replaced by fresh substrate, the process will start anew. Discontinuous dry fermentation processes are increasingly applied in fermenting bio wastes.

Continuous processes are the classical form of biogas production. They are marked by a regular (quasi-continuous) feeding into the fermenter. The drawback of this concept is the high demand for energy for operating stirring units as the content of the fermenter has to be regularly mixed. The investment costs of continuously operating plants are mostly slightly higher than those of discontinuously operating plants. Also the maintenance costs are slightly higher due to the movable stirring units. The essential advantage of continuously operating plants is the clearly higher gas output as compared with discontinuously operating dry fermentation plants. In Germany preferably continuous processes are applied in agricultural plants, with the substrate being fed into the fermenter a few times a day. Liquid (liquid manure, sludges) as well as solid substrates (maize silage, biowastes) may be used, with a sufficient water content having always to be reached in the mixture. When feeding into the fermenter an equal quantity of fermented substrate is transported from the fermenter into the next tank. Depending on the plant concept this may be a further fermenter, a secondary fermenter or a fermentation residue tank. Thus, it is possible to produce continuously biogas and thus electricity. The concept with one or a few fermenters and a fermentation residue tank is also referred to as storage-flow procedure. The predominant part of methane bacteria has optimum temperatures in the mesophilic range of approx. 30°C to 40°C. The bulk (85 %) of biogas plants in Germany is operated at this temperature range which can cope with temperature variations of ± 3 K without having great negative effects. The operation of the plants is essentially more sensitive in the thermophilic range (50°C to 57°C). Here, the temperature variations have to be limited to ±1 K as in the case of variations of a few degrees a drastic decline of the conversion rates and thus of the biogas production is to be expected. If high flow rates are striven for and the substrates used are a hygienically problematic material (bio wastes) the thermophilic process will be of advantage.

Substrates for biogas production

By tradition notably liquid and liquified excrements of cattle, pigs and poultry are used as basic substrate for many biogas plants as they are easy to handle due to being pump able. In addition, liquid manure is an ideal substrate due to its biochemical properties. It has a high buffering capacity, contains sufficient micronutrients in an available form and makes available the required bacteria population for the anaerobic fermentation. This refers notably to liquid cattle manure. In addition to liquid also solid substrates may be added to fermentation as e.g. solid manure, silages from green mass (maize silage), vinasse and pomace, rapeseed cake, plant residues and municipal bio wastes. Figure 4.

Anaerobic digestion

Anaerobic digestion (AD) is the degradation of organic materials by microorganisms in the absence of oxygen. It is a multi-step biological process where the organic carbon is mainly converted to carbon dioxide and methane [5]. The process can be divided into four steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Figure 5 shows the pathway of anaerobic digestion.

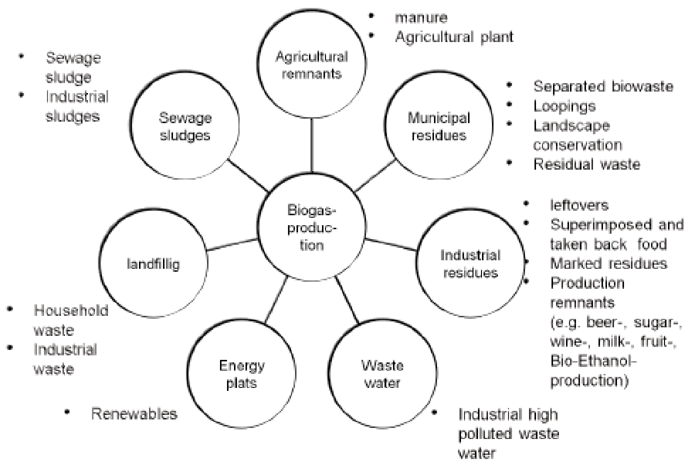

Figure 4: Substrates for biogas production

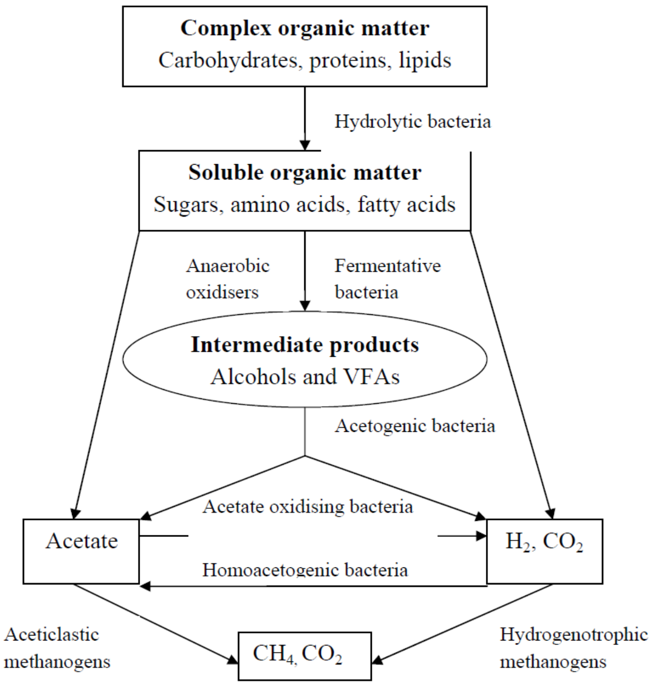

Figure 5 Pathway of anaerobic digestion (adapted from Angelidaki et al., 2002[6])

(1)Hydrolysis

Hydrolysis is the first step in anaerobic digestion processes. During the hydrolysis step, complex organic matters, such as carbohydrates, proteins and

- **Complex organic matter:** Carbohydrates, proteins, lipids
- **Soluble organic matter:** Sugars, amino acids, fatty acids, Acetate H2, CO2, CH4, CO2.
- **Intermediate products:** Alcohols and VFAs, Acetate oxidising bacteria, Homoacetogenic bacteria, Hydrolytic bacteria, Fermentative Bacteria, Acetogenic bacteria, Aceticlastic, methanogens, Hydrogenotrophic, methanogens, Anaerobic oxidizers.

Lipids are hydrolyzed into soluble organic molecules such as sugars, amino acids and fatty acids by extracellular enzyme, i.e. cellulase, amylase, protease or lipase [7]. Hydrolytic bacteria, which hydrolyze the substrate with these extracellular enzymes, are facultative anaerobes. Hydrolysis can be the rate-limiting step if the substrate contains large molecules (particulates) with a low surface-to-volume ratio [8]. While if the substrate is readily degradable, the rate-limiting step will be acetogenesis and methanogenesis [9]. When the substrate is hydrolyzed, it becomes available for cell transport and can be degraded by fermentative bacteria in the following acidogenesis step.

(2) Acidogenesis

In the acidogenesis step, the soluble organic molecules from hydrolysis are utilized by fermentative bacteria or anaerobic oxidizers [10]. These microorganisms are both obligate and facultative anaerobes. In a stable anaerobic digester, the main degradation path way results in acetate, carbon dioxide and hydrogen. The intermediates, such as volatile fatty acids and alcohols, play a minor role. This degradation path way gives higher energy yield for the microorganisms and the products can be utilized directly by methanogenic microorganisms [11]. However, when the concentration of hydrogen and formate is high, the fermentative bacteria will shift the path way to produce more reduced metabolites [6]. The products from acidogenesis step consist of approximately 51% acetate, 19% H2/CO2, and 30% reduced products, such as higher VFA, alcohols or lactate [6]. Acidogensis step is usually considered the fastest step in anaerobic digestion of complex organic matter [8].

(3) Acetogenesis

Intermediates formed during acidogenesis, consist of fatty acids longer than two carbon atoms, alcohols longer than one carbon atom and branched-chain and aromatic fatty acids. These products cannot be directly used in methanogenesis and have to be further oxidized to acetate and H2 in acetogenesis step by obligated proton reducing bacteria in a syntrophic relationship with hydrogen utilisers. Low H2 partial pressure is essential for acetogenic reactions to be thermodynamically favorable [11]. The products from acetogenesis are then the substrates for the last step of anaerobic digestion, which is called methanogenesis.

(4) Methanogenesis

In methanogenesis step, acetate and H2/CO2 are converted to CH4 and CO2 by methanogenic archaea. The methanogenic archaea are able to grow directly on H2/CO2, acetate and other one-carbon compound, such as formate and methanol [11]. In the normal anaerobic digesters, acetate is the precursor for up to 70% of total methane formation while the remaining 30% originates from H2/CO2 [12]. Moreover, the inter-conversion between hydrogen and acetate, catalyzed by homoacetogenic bacteria, also plays an important role in the methane formation pathway. Homoacetogens can either oxidize or synthesize acetate depending on the hydrogen concentration in the system [13]. Hydrogenotrophic methanogenesis functions better at high hydrogen partial pressure, while aceticlastic methanogenesis is independent on hydrogen partial pressure. At higher temperatures, the acetate oxidation pathway becomes more favorable [11]. It has been reported that methane formation through acetate oxidation can contribute up to 14% of total acetate conversion to methane under thermophilic conditions (60 °C) [14].

Factors affecting the biogas process

The factors affecting the biogas production are mainly caused by the characteristics of the feedstock and operating condition of the process. Sometimes feedstock itself can contain inhibitors such as high concentrations of cations. Other times toxic compounds are not initially present in the feed, but are produced during the anaerobic digestion process, such as VFAs. Factors from the feedstock (i.e. nutrients, pH, buffering capacity and inhibitory compounds), and operating conditions (i.e. temperature and OLR), influence directly on the performance of microorganisms.

(1) Temperature

Anaerobic digestion can be applied in a wide range of temperatures from psychrophilic (<20 °C) to extreme-thermophilic conditions (>60 °C) [15-17]. Increasing temperature has several advantages: it can increase solubility of organic compounds; increase chemical and biological reaction rates; improve diffusivity of soluble substrate; increase death rate of pathogenic bacteria, especially under thermophilic condition; increase the degradation of long chain fatty acids, VFAs and other intermediates etc. [18]. The disadvantage of high temperature can be that it decreases pKa of ammonia, thus increases the fraction of free-ammonia which is inhibitory to microorganisms and increases pKa of VFA, which increases its un-dissociated fraction, especially at low pH (4-5) such as in the acidogenic reactor [18] This is the reason why, the thermophilic process is in general more sensitive to inhibition. In our study, while digesting POME and deoiled POME, we applied 55 °C to UASB and EGSB reactor operation. Despite the high temperature advantages, another important reason is that POME has an initial temperature of 80-90 ºC [19] from oiling process and deoiled POME can have the temperature 45-50 ºC after de-oiling from POME. Therefore operating the reactor under thermophilic condition will be more economical than mesophilic condition, in terms of the ability to use a smaller digester and obtain a better methane production. For example, we observed a methane yield of 600 mL-CH4/gVS-added with deoiled POME in UASB reactor, which accounted for 98% of the theoretical methane yield. In this case, almost all the organics in the deoiled POME was digested at 55 °C in high-rate system.

(2) Nutrients

Efficient biodegradation requires nutrients and sufficient nutrients are therefore important to microbial cell growth. Macro- nutrients such as carbon, nitrogen, potassium phosphorus, sulphur [20] and micro-nutrients such as Fe, Ni, Zn and Co in smaller amount [21] are required for optimal anaerobic microbial growth. In our study, all nutrients were generally mixed as basic anaerobic (BA) medium [22] which was introduced in the digestion of POME and deoiled POME to provide enough nutrient for starting up the AD process. However, from the economical point of view, in the large industrial scale operation, the need for these supplements according to different waste characteristics should be further investigated, in order to reduce the operational cost.

(3) pH and buffering capacity

Many groups of microorganisms have the same optimal pH range, while each group has a specific pH region for optimal growth in anaerobic degradation. Methanogenic archea can function in quite narrow pH interval from 5.5-8.5 with an optimal range of 6.5-8.0 [18]. Fermentative bacteria can function in wider pH range pH 4 to 8.5 [23] and have different optimal pH in respect to the fermentation products [24]. In a mixed-culture anaerobic digester, the optimal pH range is 6.6-7.8 [25]. Knowledge in pH and factors causing or resisting to pH change is essential to control and secure a successful operation in an AD system. Buffering capacity (also called alkalinity) is an important factor for process stability, in terms of resistance to pH change. The main buffer in anaerobic digesters is bicarbonate (HCO3 -), with a pKa of 6.3, and the main generated acids are VFAs, with an aggregate pKa around 4.8 [18]. Other compounds such as hydrogen sulphide (pKa 7.1), dihydrogen phosphate (pKa 7.2), and ammonium ion (pKa 9.3) are commonly found in the digester which influence the pH balance if present at high concentrations [26].

(4) Volatile fatty acids (VFA)

VFAs are some of the most important intermediates in the anaerobic biogas process; it is the conversion from VFA into methane and carbon dioxide which is important [27]. The increase of VFA concentration in the biogas process is well-known, as a result of process imbalance. Thus, it has been commonly suggested as an indicator in the anaerobic digester [26 - 28].

(5) Organic loading rate (OLR)

Most industrial organic wastes contain a high fraction of easily degradable organic matters, which results in high methane yield, however also leads to high VFA production. It is therefore important to control OLR to maximize the biogas production.

Ecological Advantages of Biogas Technology

An easier situation can be found when looking at the ecological effects of different biogas utilization pathways. The key assumptions for the comparison of different biogas utilisation processes are:

• Biogas utilisation in heat demand controlled gas engine supplied out of the natural gas grid with 500 kWe - electrical efficiency of 37.5%, thermal efficiency of 42.5%, and a methane loss of 0.01.

• Biogas utilisation in a local gas engine, installed at the biogas plant with 500 kWe - electrical efficiency of 37.5%, thermal efficiency of 42.5%, and a methane loss of 0.5.

• Biogas production based on maize silage using a biogas plant with covered storage tank – methane losses were 1% of the biogas produced.

• Biogas upgrading with a power consumption 0.3 kWhe/m3 biogas - methane losses of 0.5.

Techniques for enhancing biogas production

Different methods used to enhance biogas production can be classified into the following categories:

(i) Use of additives

(ii) Recycling of slurry and slurry filtrate

(iii) Variation in operational parameters like temperature, hydraulic retention time (HRT) and particle size of the substrate

(iv) Use of fixed film/bio filters

(1) Use of additives

Some attempts have been made in the past to increase gas production by stimulating the microbial activity using various biological and chemical additives under different operating conditions. Biological additives include different plants, weeds [29], crop residues, microbial cultures, etc., which are available naturally in the surroundings .As such, generally these are of less significance in terms of their use in the habitat, however if used as additives in biogas plant could improve its performance significantly. The suitability of an additive is expected to be strongly dependent on the type of substrate.

(1.1) Green biomass

Powdered leaves of some plants and legumes (like Gulmohar, Leucacena leucocephala, Acacia auriculiformis, Dalbergia sisoo and Eucalyptus tereticonius) have been found to stimulate biogas production between 18% and 40%. Increase in biogas production due to certain additives appears to be due to adsorption of the substrate on the surface of the additives. This can lead to high-localized substrate concentration and a more favorable environment for growth of microbes. The additives also help to maintain favorable conditions for rapid gas production in the reactor, such as pH, inhibition/promotion of acetogenesis and methanogenesis for the best yield, etc. Alkali treated (1% NaOH for 7 days) plant residues (lantana, wheat straw, apple leaf litter and peach leaf litter) when used as a supplement to cattle dung resulted in almost twofold increase in biogas and CH4 production. Partially decomposed ageratum produced 43% and Euphorbia tirucalli L. produced 14% more gas as compared to pure cattle dung found that the addition of the tomato-plant wastes to the rabbit wastes in proportion higher than 40% improved the methane production. Crop residues like maize stalks, rice straw, cotton stalks, wheat straw and water hyacinth each enriched with partially digested cattle dung enhanced gas production in the range of 10–80%

(1.2) Microbial strains

Strains of some bacteria and fungi have also been found to enhance gas production by stimulating the activity of particular enzymes. Cellulolytic strains of bacteria like actinomycetes and mixed consortia have been found to improve biogas production in the range of 8.4–44% from cattle dung. All the strains exhibited a range of activity of all the enzymes involved in cellulose degradation, viz. C1 enzyme, exglucanase, endoglucanase, b glucosidase. It seemed that endoglucanase activity was of central importance for the hydrolysis of cellulose.

(1.3) Inorganic additives

Several inorganic additives that improve gas production have also been reported. Shimi zu (1992)[30] claimed that higher concentration of bacteria could be retained in the digester by the addition of metal cations since cations increase the density of the bacteria, which are capable of aggregating by themselves. The addition of iron salts at various concentrations [FeSO4 (50 mM), FeCl3 (70 lM)] have been found to enhance gas production rate. Nickel ions (2.5 and 5 ppm) enhanced biogas up to 54% due to the activity of Ni-dependent metallo-enzymes involved in biogas production. Addition of rock phosphate (RP) proved superior to single super phosphate (SSP) while digesting rice straw in batch fermenters Process stability increased with increasing levels of silica gel, indicating that volatile acids were consumed at a faster rate in the presence of an adsorbent. Using Ca and Mg salts as energy supplements, CH4 production was enhanced and foaming was avoided.

(2) Gas enhancement through recycling of digested slurry/slurry filtrate

The recirculation of digested slurry back into the reactor has been shown to improve the gas production marginally, since the microbes washed away are reintroduced back into the reactor, thereby providing an additional microbial population. The recycling of the digested slurry along with filtrate has also been tried out to conserve water and to enhance biogas production.

(3) Variation in operational parameters

The performance of biogas plant can be controlled by studying and monitoring the variation in parameters like pH, temperature, loading rate, agitation, etc. Any drastic change in these can adversely affect the biogas production. So these parameters should be varied within a desirable range to operate the biogas plant efficiently.

(**3.1) Temperature**

(3.1.1) Effect of temperature on biogas production

Temperature inside the digester has a major effect on the biogas production process. There are different temperature ranges during which anaerobic fermentation can be carried out: psychrophilic (<30 _C), mesophilic (30–40 _C) and thermophilic (50–60 _C). However, anaerobes are most active in the mesophilic and thermophilic temperature range. The length of fermentation period is dependent on temperature.

(3.1.2) Installation technique for getting optimum temperature conditions

Most of the remedies mentioned in the literature to enhance biogas production are aimed at increasing the digester temperature to mesophilic range (i.e. optimum temperature). It is noted that systematic studies on bio methanation by psychrophilic micro flora are lacking. Some precautions taken during the installation of biogas plants and coating them with insulating materials also helps in keeping the temperature in the digester within the desired range. In order to increase gas yield, it is preferred to construct biogas plants sun-facing and in a manner as to protect them from cold winds. Biogas plants should be covered with locally available crop residues for minimizing heat losses from the plants.

(3.2) pH

pH is an important parameter affecting the growth of microbes during anaerobic fermentation. pH of the digester should be kept within a desired range of 6.8–7.2 by feeding it at an optimum loading rate. The amount of carbon dioxide and volatile fatty acids produced during the anaerobic process affects the pH of the digester contents. For an anaerobic fermentation to precede normally, concentration of volatile fatty acids, acetic acid in particular should be below 2000 mg/l.

(3.3) Pretreatment

Feed stocks sometimes require pretreatment to increase the methane yield in the anaerobic digestion process. Pretreatment breaks down the complex organic structure into simpler molecules which, are then more susceptible to microbial degradation. Pretreatment could be done in any of the following ways:

(i) Pretreating the feedstock with alkali or acid
(ii) Predigestion of fresh substrate
(iii) Thermochemical pretreatment
(iv) Ultrasonic pretreatment
(v) Ensilage of feed

(3.4) Particle size

Though particle size is not that important a parameter as temperature or pH of the digester contents, it still has some influence on gas production. The size of the feedstock should not be too large otherwise it would result in the clogging of the digester and also it would be difficult for microbes to carry out its digestion. Smaller particles on the other hand would provide large surface area for adsorbing the substrate that would result in increased microbial activity and hence increased gas production.

(3.5) C:N ratio

It is necessary to maintain proper composition of the feedstock for efficient plant operation so that the C:N ratio in feed remains within desired range. It is generally found that during anaerobic digestion microorganisms utilize carbon 25–30 times faster than nitrogen. Thus to meet this requirement, microbes need a 20–30:1 ratio of C to N with the largest percentage of the carbon being readily degradable. Waste material that is low in C can be combined with materials high in N to attain desired C:N ratio of 30:1. Some studies also suggested that C:N ratio varies with temperature.

(3.6) Agitation

Stirring of digester contents needs to be done to ensure intimate contact between microorganisms and substrate which ultimately results in improved digestion process. Agitation of digester contents can be carried out in a number of ways. For instance daily feeding of slurry instead of periodical gives the desired mixing effect. Stirring can also be carried out by installing certain mixing devices like scraper, piston, etc. in the plant. It is possible to achieve mixing effect by incorporating a nozzle for flushing slurry as provided in the German design of Schmidt–Eggersgluss type biogas plant.

(3.7) Seeding of biogas plant

It is often necessary to introduce enriched seeding bacteria into the digester for starting up the anaerobic fermentation process. Generally digested sludge from a running biogas plant or a municipal digester, material from well-rotted manure pit, or cow dung slurry is used as seed. If during the operation volatile fatty acids are accumulated due to overloading, this can be corrected by reseeding and temporarily suspending the feeding of digester or by adding lime in requisite quantities. Addition of inoculum tends to improve both the gas yield and methane content in biogas. It is possible to increase gas yield and reduce retention period by addition of inoculums.

(3.8) Organic loading rate (OLR)

Gas production rate is highly dependent on loading rate. Methane yield was found to increase with reduction in loading rate. In an another study carried out in Pennsylvania on a 100 m3 biogas plant operating on manure, when OLR was varied from 346 kg VS/day to 1030 kg VS/day, gas yield increased from 67 to 202 m3/day. There is an optimum feed rate for a particular size of plant, which will produce maximum gas and beyond which further increase in the quantity of substrate will not proportionately produce more gas.

(3.9) Hydraulic retention time (HRT)

HRT is the average time spent by the input slurry inside the digester before it comes out. In tropical countries like India, HRT varies from 30–50 days while in countries with colder climate it may go up to 100 days. Shorter retention time is likely to face the risk of washout of active bacterial population while longer retention time requires a large volume of the digester and hence more capital cost. Hence there is a need to reduce HRT for domestic biogas plants based on solid substrates.

(3.10) Solid concentration

The amount of fermentable material of feed in a unit volume of slurry is defined as solid concentration. Ordinarily 7–9% solids concentration is best-suited. The biogas yield increased, reaching 0.46 m3/(m3 day) at 37 _C and 0.68 m3/(m3 day) at 55 _C respectively.

(4) Bio filters / fixed film reactors

Fixed film reactors have been used since long for the treatment of wastewater where they have helped to reduce the HRT from 30–40 days to a few hours. These reactors come under the category of advanced reactors like UASB, fluidized bed, up flow anaerobic filters, etc. They help in enhancing the performance of wastewater treatment systems by providing an increased surface area for attached growth of the microbes in the form of a fixed film on an inert medium leading to increased population of microbes in the reactor and their retention in the digester even after the digested slurry flows out. Fixed film technique has been used commonly for substrates of very low solids content where filters of very large surface area are used.

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