Biodigesters: chemical, physical and biological factors related to their productivity

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Key words

Biogas; biodigester; methane productivity; substrates; methanogenic bacteria.

Abstract

Biodigesters are designed to optimize biogas production using organic wastes, thereby attaining clean, low-cost renewable energy. In 2008, a group of ITCR researchers worked on developing a wireless electronic system for control and protection of biogas production. One of the specific objectives of this work was to find information about methods to increase biogas production. In this review we established the mathematical parameters related to biogas estimation of productivity. We then focused on the influence of chemical factors such as substrate composition, substrate combinations, addition of fat, and presence of inhibitors. We also studied the effect of physical factors such as temperature, solids removal, protein exclusion and phase separation during anaerobic digestion of organic matter. Finally we attempted to determine the role of biological factors such as the addition of thermophilic bacteria and the importance of methanogens.

Introduction

Biogas production is a natural process which takes place spontaneously in an anaerobic environment, i.e., one without oxygen. This process is caused by microorganisms as part of the biological cycle of organic matter which involves fermentation or digestion of organic matter to obtain biogas.

Biodigesters are systems designed to optimize biogas production from agricultural wastes, manure, or industrial effluents, thereby attaining clean, low-cost energy from a renewable source. Use of this technology is not new, but over the last few years it has gained interest due to the current energy crisis resulting from the exhaustion of fossil fuels. In addition, use of biogas helps reduce emissions of greenhouse gases such as methane (CH_4), whose potential for global warming is 23 times higher than that of carbon dioxide (CO_2) (Campero et al., 2008).

In countries such as Germany and France, biogas is used as a fuel for motor vehicles. However, in Costa Rica and other developing countries, use of biogas has been limited to those locations where it is produced, where it may be used directly for combustion for cooking or lighting, or indirectly, to drive internal combustion engines that generate engine or electrical power (Kapdi et al., 2004; Ilyas, 2006).

At the Instituto Tecnológico de Costa Rica (ITCR) a project financed by the Research Vicerectory (VIE) was implemented in 2008. Its aim was to develop a control and protection wireless electronic system to monitor the production, compression, and storage of biogas from a biodigester. One of the specific objectives of the project was to research on methods for speeding decomposition of raw matter and increasing gas production.

The mathematical parameters related to biodigester productivity are presented in this document. Additionally, several chemical, physical and biological factors affecting this process are discussed.

Mathematical parameters related to productivity of a biodigester

One of the parameters to estimate biogas production in a biodigester is methane productivity or methanoic productivity. This is defined as the amount of methane generated in a unit of time from the material placed in the reactor. The mathematical expression to calculate methane productivity of a given organic waste in a given time is as follows (Sogari, 2003):

$$P_{CH4} = \frac{V_{CH4}}{V_{reactor} * t}$$

Where V_{CH4} is the methane volume generated; $V_{reactor}$ is the volume of matter placed in the fermentation chamber and t is the time for production to place.

Methane production is limited by the nature of the matter placed in the digester system. The formula to estimate the maximum methane generation for a certain product is as follows (Sogari, 2003):

$$M_{Max} = \frac{V_{CH4}}{S_{org\ total}}$$

Where V_{CH4} is the volume of methane generated, and $S_{org\ total}$ is the total amount of organic matter used in the process.

In following sections of this document, an in-depth analysis is presented concerning the influence of chemical factors such as substrate composition, substrate combinations, addition of fat, and presence of inhibitors on biodigester productivity.

II. Chemical factors

1. Substrate chemical composition

The ideal substrates for anaerobic digestion in biodigesters are moist organic wastes from agricultural, industrial, domestic, and municipal activities, as well as human and animal excrement. Residues from the food industry and agricultural activity in particular, are excellent substrates for anaerobic digestion since they do not contain pollutants, pathogenic agents, or heavy metals.

The presence of nutrients such as carbon, nitrogen and sulphur, as well as some trace elements, is necessary for growing microbial communities that produce biogas. The carbon-nitrogen proportion must be of 20-30 parts of carbon for every part of nitrogen. If the share of nitrogen increases, biogas production may decrease due to the formation of ammonia, which is generated during the anaerobic degradation of urea or proteins. Free ammonia may inhibit anaerobic fermentation, and is toxic for methanogenic bacteria (Guevara, 1996; Gallert and Winter, 1997; Cui and Jahng, 2006).

It is not recommended to use a single type of substrate. To the contrary, it is ideal to combine nitrogen-rich materials with carbon-rich materials to obtain a balance of nutrients which will promote growth of organic matter-degrading microorganisms inside the biodigester, thereby increasing its productivity (Guevara, 1996).

2. Substrate combinations

Since 1999, German biogas-producing plants have mixed animal excreta with industrial residues from food, agriculture, markets, restaurants, and the municipal sector. Productivity of bovine and porcine excreta used as biomass ranges from 25-36 m^3/ ton of fresh mass, since their content of dry organic matter is low (2-10 %). In addition, their carbon/nitrogen ratio is below 25:1, i.e., they are nitrogen-rich. Meanwhile, biogas production from crops such as forage beets, corn, sweet sorghum and barley, is from -1000m^3 per ton of dry organic mass. The carbon/nitrogen ratio of these substrates is above 30:1, i.e., they are carbon-rich. Co-digestion of these crops results not only in a strong increase in biogas productivity, but also in a reduction of trace elements in digested residues (Martínez et al., 2008; Gleixner, 2007; Weiland, 2000; Guevara, 1996).

Rodríguez et al. (1997) analyzed productivity of a combination of manure with the plant *Eichornia crassipes*, and of each substrate separately, and found that digesters to which *E. crassipes* were added showed the greatest productivity, while those containing manure were less productive. When both substrates were combined, the authors found that adding *E. crassipes* improved manure productivity.

These studies reinforce the concept of combining different types of substrates to balance the proportion of nutrients available for microbial communities responsible for biogas production.

3. Addition of fat

Vegetable fats have a high energy potential due to their chemical composition and high content of lipids that can be degraded by anaerobic bacteria. When added to biodigesters, they may increase biogas productivity up to 2400 %. Three treatments were tested in a study conducted in Costa Rica by researchers of EARTH University. Tests consisted of adding 0%, 2.5%, and 5% of oil to a biodigester provided with porcine and bovine excreta. There was a direct increase in productivity as the percentage of oil was increased. The baseline test with 0 % oil generated 244 liters of biogas; the treatment test with 2.5% oil generated 342 liters; and the treatment test with 5 % of added oil generated 477 liters (Dias et al., 2007).

Martínez (2008) warns that using animal fats may increase risk of disease transmission. He also suggests pre-treating residues from restaurants, markets, and municipalities to reduce particle size, separate potential pollutants of the digestion process, and facilitate subsequent application of anaerobically treated residues to the soil. With respect to this last point, he recommends pasteurization at 70 °C for one hour to eliminate pathogenic germs.

It may be concluded that the use of vegetable fats together with a combination of nitrogen-rich and carbon-rich substrates increases biodigester productivity.

4. Inhibitors of biogas production

In addition to free ammonia, according to García *et al*. (2006), the lineal alkylbenzene sufonate (LAS) is the most important anionic surfactant found in household and industry cleaners. In most digesters, the addition of surfactants causes a reduction of the biogas production rate.

This must be taken into account when adding household and industrial residues to a biodigester in operation, since accidental inclusion of these materials may reduce productivity rather than increase it.

III. Physical factors

1. Temperature

Anaerobic biodigestion can take place in at temperatures ranging from 5-60°C. Methanogenic bacteria are more sensitive to temperature than the other microorganisms of a biodigester, since their growth rate is slower. The anaerobic digestion process is not affected by temperature increase in a few degrees. However, a decrease in temperature may delay methane production, without damaging acidifying bacteria, causing an excessive accumulation of acids and a potential failure in the biodigester. Efforts should therefore be made to maintain a warm microclimate in the biodigester, which will in turn favor higher biogas production rates (Bidlingmaie, 2006; Osorio et al., 2007).

A strategy for increasing biodigester temperature, and keeping the temperature constant, is to build a light structure lined with greenhouse plastic, which will also help to exclude animals that might damage it.

2. Separation of solids

Impurities such as plastic or sand should be separated out through flotation and sedimentation techniques. In addition, a reduction in size of solid waste particles to 10-40 mm is necessary to achieve better biological accessibility and substrate flow (Weiland, 2000). According to Kasapgil et al. (2001), use of unsupported tubular membranes for ultrafiltration, joined to the biodigester as an external unit, produces a significant increase in the amount of biogas with energy value produced.

This is a low-cost measure that may be easily implemented at the entrance of any biodigester.

3. Protein extraction from sludge

Cui and Jahng (2006), found that disintegration of sludge and subsequent extraction of proteins significantly improved biogas generation, as well as the content of methane in the biogas produced from deproteinized sludge, which rose from 55.6% (v/v) (control) to 74.8%. This is because from 40-50 % of the dry weight of a microbial cell consists of proteins which generate ammonia. As mentioned previously, free ammonia inhibits biogas production because it is toxic for methanogenic bacteria. Therefore, extraction of proteins from sludge may optimize both biogas production and quality.

The authors of this study conducted deproteinization of the sludge through thermal treatment at 121ºC, by sonication (use of ultrasound waves), and by denaturing alkaline pH. Of these alternatives, the least feasible to apply in Costa Rica is sonication, since expensive equipment would have to be acquired.

4. Separation of phases

Overall, around 70% of biomass is converted to methane (CH_4) and carbon dioxide (CO_2). To increase this percentage, a separation of the phases that make up anaerobic digestion of organic matter is required – i.e., hydrolysis (degradation of complex organic composites to simple composites), acidogenesis (removal of fatty acids), acetogenesis (acetate production), and methanogenesis (methane generation). Thus, pH conditions and temperature in each process can be optimized (Gleixner, 2007; Antoni et al., 2007; Park et al. 2008.)

Kon et al. (2006) developed a modified three-phase system for methane fermentation. Semi-anaerobic hydrolysis and acidogenesis processes were carried out in the first phase. Strictly anaerobic acidogenesis was performed in the second phase, and strictly anaerobic methanogenesis was performed in the third phase. The acidic fluid produced in the secondary acidogenic fermentator was used as substrate, and the methanogenic fluid created in the methanogenic fermentator was used as inoculum. Species of *Clostridium* were used as microorganisms in the acidogenic fermentation. A mix of bacteria isolated from the soil and from cow manure was used in methanogenic fermentation. In the reaction, 8 liters of the mixture of substrate and inoculum (1:1) were placed in the methanogenic reactor. Each reactor was operated at temperatures that rose from from 30°C to 55°C in intervals of 5°C. Changes in pH, CODs and gas production were monitored. As a result, hydrolysis, acidogenesis, and methanogenesis rates were increased without affecting pH, and high levels methane production occurred.

However, in spite of the advantages mentioned in the literature, most biogas agricultural plants use a one-phase technology because its installation and maintenance are less expensive.

IV. Biological factors

1. Addition of thermophilic bacteria

The productivity of an anaerobic digestion system is mainly related to the structure of the microbial community present in the digester. The environmental and operational parameters of the process affect the behavior, productivity and –eventually– the destination of the microbial community in anaerobic digesters. Furthermore, the nature and influence of sludge used for inoculation should also be taken into account (Demirel and Scherer, 2008.) For instance, according to Miah *et al.* (2005), the addition of a small amount of aerobic thermophilic bacteria (TA) has a great potential as a cost-effective treatment to speed up anaerobic digestion of biological wastes. The addition of 5% (v/v) of methanogenic TA sludge to the methanogenic sludge increased biogas production with a methane concentration of 50-67%. This is due to the fact that, during sludge solubilization, the enzymes of excreted TA bacteria influenced the hydrolysis of the sludge during anaerobic digestion.

Nonetheless, it is necessary to have an operating temperature close to 65°C to work with TA, which increases the cost of the process.

2. Importance of methanogens

According to Demirel and Scherer (2008), differences in environmental and operating conditions affect the behavior of acetotrophic and hydrogenotrophic methanogens in a biogas digester. Acetotrophic methanogens are obligate anaerobes that convert acetate into methane (CH_4) and carbon dioxide (CO_2). Their activity and function are highly important during acetate anaerobic conversion. On the other hand, the activity of hydrogenotrophic methanogens is crucial for a stable and efficient operation of the biodigester, although hydrogen presence may be a hindering factor for these microorganisms.

To promote an increase in biodigester productivity, they may be inoculated with known sources of methanogen microorganisms such as cow's rumen, which is an effective, low-cost alternative.

Conclusion

Productivity of a biodigester is mainly related to the structure of the microbial community used in it. In addition, methane production is limited by the nature of the matter placed in the digester system.

However, through manipulation of the chemical, physical, and biological factors discussed in this document, biogas production can be easily adapted to current energy demand. It is worth highlighting those approaches that are relatively low cost, such as combination of substrates, addition of fats, separation of solids, and inoculation of biodigesters with methanogenic microorganisms.

Ongoing research to strengthen our knowledge in this area is being carried out at ITCR through a multidisciplinary project financed by the Vicerectory of Research and Outreach (VIE). There is a plan to build a polyethylene biodigester to be able to carry out field tests. Subsequent research will focus on methods for biogas purification to obtain highly purified methane that can be bottled and transported.

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