Anaerobic Digestion of Food Waste to Produce Biogas: A Comparison of Bioreactors to Increase Methane Content – A Review

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Abstract

Anaerobic digestion can be used to degrade food waste and recover energy. Methane is a biogas that can be efficiently converted in electricity. Organic loading rate, temperature, time, pH, carbon to nitrogen ratio are important factors to be operated in the bioreactors and still are challenges in this process to increase biogas production. It has been reviewed the single phase and two-stage bioreactors in the anaerobic digestion of food waste as well organic loading rates and the rate of methane produced.

Keywords: Biomass; Biogas; Anaerobic digestion; Bioreactors

Introduction

The reduction of CO₂ emissions, large demand of fossil fuels and environmental issues are the reasons for studies to develop new technologies to obtain energy from biomass. More attention is being directed toward biological production of biogas using anaerobic digestion processes.

According the Natural Resources Defense Council [1,2], more than 40% of the food in the United States is wasted during crop, production, transportation and final consumer, which accounts for $165 billion each year going to trash. Moreover, most of this food waste ends up in landfills releasing methane to the atmosphere.

Biomass is organic matter from agricultural crops and wastes, animal wastes, forest and wood residues, plants and municipal waste and it is stored as chemical energy. This energy can be released as biogas such as methane (CH₄), hydrogen (H₂) and carbon dioxide (CO₂) through the anaerobic digestion process [1].

Food wastes are rich in organic matter and as they release methane, a greenhouse gas. Feedstock characteristics (Table 1), reactor design and conditions of operation play the major role in the bio gas production and process stability in anaerobic digestion process. Food waste treatment and its conversion into biogas is carried out in single-phase and high-rate two-phase anaerobic digestion processes where microorganisms breakdown biodegradable material in the absence of oxygen [3].

Anaerobic digestion

Anaerobic Digestion (AD) occurs in the absence of oxygen and produces methane for energy recovery and treats waste for environmental benefits. It is being applied to food waste, one of the largest waste streams going to landfills.

Figure 1 illustrates the process where the first two steps are operating within defined parameters ensures optimal biogas production.

In the United States is more often used mesophilic digester due to lower capital and ease of operation and this digester operates in the range of 35°C to 40°C. The length of time the food waste will degrade entirely in the digester depends on the temperature, process system, and its properties. Organic loading rate (OLR) refers to the rate at which volatile solids (VS) are added to a digester. It is calculated by dividing pounds of volatile solids added to the digester daily by the digester volume [4,5]. The OLR of VS has to be standardized in order to maximize methane production and avoid the system to shut down.

It is needed relative residence time for full degradation. The effects of stepwise increase in OLR on integrated two stage systems and Kondusamy and Kalamdhad [6] stated that at steady state the optimal OLR would be 22.65 kg VS/m²d (160 h) for hydrogen fermentation reactor and 4.61 for methane fermentation reactor. In a single stage reactor it was found an OLR of 9.2 kg VS/m²d with a high VS reduction of 91.8% and high methane yield of 455 ml/g/VS/d.

Characteristics of food waste reported by Zhang et al. [7] (Tables 2 and 3), that the physical and chemical composition are important information for design reactors and process stability during anaerobic digestion. This information include moisture content (MC), volatile solids content (VS), nutrient content, particle size and biodegradability. Under a given temperature and certain amount of time, the amount of methane and biogas produced is measured.

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy content</td>
<td>1,500-3,000 btu/lb</td>
</tr>
<tr>
<td>Density</td>
<td>2,000 pounds per cubic yard</td>
</tr>
</tbody>
</table>

Table 1: Food waste characteristics.

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Grimberg et al. highlight that two stage digester for food waste treatment is stable while highly variable loading. Also, two stage systems are more efficient for resolving pH inhibition issues of one stage systems.

**Experimental Work**

Two-phase anaerobic digester system has an acidogenic reactor in the first phase which maintains the low pH and short hydraulic residence times (2-3 times) and produces hydrogen and a methanogenic reactor in the second phase that is operated at HRT of 20-30 days and pH of 6-8 to produce methane. Kondusamy and Kalamdhad [6] reported that the overall gas production rate of the two stage reactor if four times greater than the single phase reactor. In this study was evaluated the amount of food waste digested anaerobically resulting in potential 367 m³ of biogas per dry ton with 65% of methane.

Experiments were conducted by Zhang et al. [7] at 50°C, single stage reactor with OLR of 6.8 and 10.5 VS⁻¹ the results were 2.56% TS, 83% VS/TS and 70% MC. The C/N ratio obtained was 14.8 and 435 ml/g VS of methane yield after 28 days.

Grimberg et al. [8] had the research done in both single and two stages reactors, loading the single system with 50% capacity for 6 months and with 20% capacity the acid fermentation reactor. The methanogenesis reactor was loaded with 90% capacity receiving effluent from the fermentation reactor. The average digester loading for the single stage system was 28.89-27.76 kg day⁻¹ and 25.26-35.31 kg day⁻¹ for the two stage system. The temperature for both reactors was maintained in 37.4°C. The methane yield was 380 and 446 LCH4 KgVS⁻¹ for one stage reactor and two stage reactors respectively.

**Results and Discussion**

Experiments with food waste showed that after digestion at retention times of 10 and 28 days, the methane yield was determined to be 348 and 435 ml/g volatile solids (VS), respectively. The average methane content was 73%, with an average VS destruction of 81% at 28 days of digestion. It indicates that the food waste is highly desirable for anaerobic digestion, due to its high biodegradability, nutrient content, and methane yield [3].

Zhang et al. [7] reported 66-73%, 23% and 84-87% VS/TS for MC, VS and VS/TS respectively. The range of MC shows that sufficient moisture contained in the food waste to carry out anaerobic digestion. After 28 days of digestion with 6.8 and 10.5 g VS/L the methane yield average was 435 ml/g VS at 50°C. The biogas composition can be assumed to be 73% methane content and 37.3 MJ/m³ and C/N 14.8.

The acidification reactor operates with a retention time of 5 days and at a pH of 6.5, while the methane phase reactor operates with a retention time of 15 days and in a pH range of between 7.4 and 7.8. Maximum organic loading rate was determined to be 7.9 kg VS/m³ day⁻¹, and the methane content in biogas was around 70% [3].

Grimberg et al. [8] observed no significant difference in the effluent concentration of both systems with average removal of VS 96% in single stage and 93% for two stage systems. Also, the methane production was higher in the two stage reactor than in the single one when the gas production was normalized to the feedstock input. Therefore, the fermentation stage serves as an equalization buffer in the event of shock loading, providing safety for the anaerobic digester system.

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**Table 2: Characteristics of food waste.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>95-105°F</td>
<td>Mesophilic</td>
</tr>
<tr>
<td></td>
<td>125-140°F</td>
<td>Thermophilic</td>
</tr>
<tr>
<td>pH</td>
<td>6.5-7.5</td>
<td>Ideal pH is neutral at 7.0. Self-regulating by anaerobic microbi; methanogens unlikely to grow with pH &lt; 6.5</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>0.133 ounce/gallon</td>
<td>Self-regulating by hydrogen in waste converting to Biocarbonate</td>
</tr>
<tr>
<td>Acidity to Alkalinity Ratio</td>
<td>0.3 to 0.5</td>
<td>Easier to measure than VFA or alkalinity</td>
</tr>
<tr>
<td>Volatile Fatty Acids (VFA)</td>
<td>&lt;0.013 ounce/gallon</td>
<td>Higher concentrations will inhibit acetate and biogas production</td>
</tr>
<tr>
<td>Carbon to Nitrogen Ratio</td>
<td>20 to 30</td>
<td>Higher C/N ratios result in methogens consuming nitrogen; lowering biogas production</td>
</tr>
<tr>
<td>Organic Loading Rate</td>
<td>3-5 kg of Volatile Solids per cubic meter of digester volume per day</td>
<td>Microbes are generally inhibited if loading rate exceeds 6.4 kg/m³ day⁻¹</td>
</tr>
<tr>
<td>Residence Time</td>
<td>9-95 days</td>
<td>Varies widely based on feedstock, temperature, and system design</td>
</tr>
</tbody>
</table>

**Table 3: Anaerobic Digestion Operating Parameters.**

The retention time is the time the microorganisms survive in the system. Methanogen bacteria are essential for AD, as these microorganisms grow slow, any changes in AD parameters should be slow to maintain the bacteria alive [4].

AD technologies are typically optimized for either low solids or high solids content. Alternatively, they are referred to as wet or dry even though the feedstock generally has moisture content above 70%. Low solids refer to wastes with solid content of 3%-10%, and high solids refer to solid content of 15% or more. Wet digesters slowly mix feedstock with microbes to increase the speed of degradation. Water will need to be added to food wastes in a wet digester to reduce solids content [5].

**Reactors**

Single stage reactors have the hydrolysis, acidogenesis, acetogenesis and methanogenesis happening at the same place. It can have the acidification of the digestor due to shock loading.

Two stage reactors have the hydrolysis and acidogenesis taking place in an initial reactor and then these acids are used by methanogenesis in the final reactor. According Kondusamy and Kalamdhad [6] the two stage reactor is more efficient because the dynamics of the process allows the individual bacterial species to separate from hydrolysis and methanogenesis.
Conclusions

Research has demonstrated that a two-stage reactor leads to higher biogas and methane yields if compared to a single stage reactors. However, dual reactors increase construction and materials costs while single-stage systems are more common due to lower capital costs. Based on research, it is suggested that anaerobic digestion of food waste to recover energy depends on optimal conditions, temperature and methodology as well the feedstock loading. More research should be done to increase methane content in biogas and reduce costs of operation.

References