Chapter 6
Biogas from Extremophiles

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What Will You Learn from This Chapter?
This chapter provides an elementary understanding of biogas production processes and applications. The chapter covers the important parameters affecting biogas production, different types of digesters, and technology used in anaerobic digestion.

6.1 Introduction

Biogas is a mixture of methane and carbon dioxide produced as a result of anaerobic digestion (AD) of organic compounds. The methane fraction in the biogas is an energy-rich compound (~39.4 MJ/m^3), which can be used for different applications including cooking, heating, and electricity production and also can be used as fuel for vehicles. The history of biogas dates back to 3000 BC, where the Sumerians used the anaerobic digestion concepts to treat waste. Later in 1776, Alessandro Volta collected the gas from a lake and reported that the gas formation was due to a fermentation process and it can form an explosive mixture in the presence of air. However, only in 1821, the structure of methane was first elucidated. In 1897, Pasteur reported the first application of biogas by electrifying street lamps using biogas from wastewater treatment. Since then the application and market for biogas are widely increasing (Deublein and Steinhauser 2008).

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Biogas production can be divided into four different phases including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first phase, the complex substrates are broken down into their monomeric forms and long-chain fatty acids, for instance, cellulose to glucose, proteins to amino acids, and fats into fatty acids. In acidogenesis, the monomers and long-chain fatty acids are converted into short-chain volatile acids including valeric acid, propionic acid, and butyric acid. The short-chain acids are further converted into acetic acid, hydrogen, and carbon dioxide in acetogenesis phase. Finally, the products of acetogenesis are converted to methane and carbon dioxide in the methanogenesis phase. Approximately 70% of the biogas production is obtained from the acetic acid conversion and 30% from the hydrogen and carbon dioxide pathway in the acetogenesis phase (Rajendran et al. 2013).

The biogas is usually produced at three different temperature ranges: psychrophilic <25 °C, mesophilic 25–35 °C, and thermophilic >45 °C. The scope of this book is limited to extremophiles, and hence the main focus of this chapter will be on psychrophilic and thermophilic anaerobic digestion. This chapter focusses on anaerobic digestion from extremophiles including different process parameters and digester designs. Nextly, a comparative assessment of two extremophilic conditions, i.e., psychrophilic and thermophilic, was discussed. Later, the technology-wise comparison was made based on solids loading. The last section of this chapter covers on the overview on applications and economic outlook on biogas productions (Deublein and Steinhauser 2008).

6.2 Substrates

In theory, any organic substrate or biomass can be used for biogas production when they contain carbohydrates, proteins, fats, cellulose, and hemicelluloses. Some of the conventional substrates for biogas production include cattle manure, MSW, sludge, and food waste. Recently, certain new substrates are being explored including seaweeds, algae, and water hyacinth, and in addition sometimes a mixture of the substrate is used in the same digester called as co-digestion. In co-digestion systems, optimal C/N ratio and nutrient balance can be achieved, which leads to a higher biogas productivity (Al Seadi 2008).

There are certain factors which need to be considered when choosing a substrate for biogas production:

1. Content of organics in the substrate
2. Nutritional value
3. Pathogen-free substrates
4. Less heavy metals and other hazardous content
5. Expected methane content for further application
6. Treatment of digestate as a fertilizer

Table 6.1 Different substrates and their biogas yield

Substrate	Substrate classification	Dry matter (%)	Ash (%)	Biogas yield
Manure	Cow	38	14	0.6–0.8 m^3/kg TS
	Pig	20–25	NA	0.27–0.45 m^3/kg TS
	Poultry	89	33	0.3–0.8 m^3/kg TS
	Horse	28	NA	0.4–0.6 m^3/kg TS
Agricultural residues	Rice straw	91	13	0.55–0.62 m^3/kg TS
	Wheat straw	91	8	0.18 m^3/kg VS
	Maize straw	86	NA	0.4–1.0 m^3/kg TS
	Grass	88	6	0.28–0.55 m^3 /kg VS
	Corn stalk	80	7	0.35–0.48 m^3/kg VS
	Cassava peels	NA	NA	0.66 m^3/kg VS
Food wastes	Vegetable waste	5–20	NA	0.4 m^3/kg TS
	Kitchen/restaurant wastes	27/13	8	0.50/0.65 m^3 CH_4/kg VS
	Leftovers	14–18	NA	0.20–0.50 m^3/kg TS
	Food	25	NA	0.97–0.98 m^3/kg TS
Aquatic plants or seaweeds	Algae	NA	NA	0.38–0.55 m^3/kg VS
	Water hyacinth	7	NA	0.2–0.3 m^3/kg VS
	Caboma	NA	NA	0.22 m^3/kg VS
	Salvinia	NA	NA	0.15 m^3/kg VS

The list of some of the substrates and their expected biogas yield are provided in Table 6.1.

6.3 Process Parameters

6.3.1 Organic Loading Rate (OLR)

The organic loading rate (OLR) defines the load or the material intake that a reactor can handle. Usually, this is a design parameter, and it is in the correlation between HRT, biogas yield, and economics of the biogas plant. The OLR for the psychrophilic digestion varies between 0.2 and 1.2 kgVS/ m^3/day, while the thermophilic biogas production varies between 3 and 4 kgVS/m^3/day (Al Seadi 2008). The OLR can be calculated by the following equation:

$$\mathrm{OLR} = m \times c/V_R$$

where m is a mass of the substrate fed per time (kg/d), c is concentration of organics (%), and V_R is the volume of the digester (m^3).

6.3.2 Hydraulic Retention Time (HRT)

Hydraulic retention time determines the time that the organic load that stays inside the digester. The retention time determines the volume of the digester, for instance, a shorter retention time decreases the volume of the digester, while higher retention time which is often used in psychrophilic digestion increases the reactor volume. This is the reason why most psychrophilic digestion has a larger volume of the digester to treat the same amount of waste when compared to the thermophilic digestion. The HRT for the psychrophilic process varies between 60 and 80 days, while for the thermophilic process it is between 15 and 25 days (Al Seadi 2008). The HRT is given by the following equation:

$$\mathrm{HRT} = V_R/f$$

where HRT is retention time (days), V_R is volume of the digester (m^3), and f is influent flow rate (m^3/day).

6.3.3 Temperature

Temperature is another important parameter in anaerobic digestion processes. The biogas production can usually occur in three different temperature ranges: psychrophilic, mesophilic, and thermophilic digestion. The psychrophilic digestion is usually carried at temperatures less than 25 °C, and it is common in household biogas digester such as fixed dome/floating drum or balloon digesters. The mesophilic (25–35 °C) and thermophilic (>45 °C) digestion systems are quite common in industrial setups; however, the hydrolysis is more favorable in the thermophilic temperature range. In addition, the pathogens need to be treated, and if the digestion happens at a mesophilic temperature, the treatment of pathogens needs additional energy pushing the world trend toward biogas production from thermophilic digesters (Kabir et al. 2015).

6.3.4 pH

pH measures the alkalinity/acidity in the digester, and it influences the growth of microorganisms present in the digester. It also affects the dissociation of some compounds including ammonia, organic acids, sulfide, etc. Different microorganisms favor different pH, while most of the methanogens are active at pH 7.0–8.0, and the hydrolytic bacteria are active at pH 5.5–6.5. The dissolution of carbon dioxide in water decreases with the increase in temperature, and as a result of dissolution, carbonic acid is formed, which decreases the pH in the system (Deublein and Steinhauser 2008; Al Seadi 2008).

6.3.5 Volatile Fatty Acids (VFA)

The stability of the anaerobic digestion process is affected by the volatile fatty acids (VFA) including acetate, butyrate, propionate, and valerate which are formed during the different stages of anaerobic digestion. The accumulation of the VFA causes a disturbance in the system, and it is a relative unit, where the same VFA level in two different systems can act differently due to the combination of microorganisms present in the system (Deublein and Steinhauser 2008).

6.3.6 Ammonia

The amounts of ammonia present in the digester play an important role in the inhibition of the anaerobic digestion process. The free ammonia is more toxic compared to the ammonia in ionic forms. Methanogens are mostly affected by the ammonia inhibition causing turbulence in the system, and the ammonia concentration should be maintained less than 1500 mg/l for an optimum process. The ammonia inhibition is about to happen more in thermophilic temperatures than mesophilic anaerobic digestion (Al Seadi 2008). The ammonia inhibition is calculated by the following equation:

$$NH_3 = \frac{T - NH_3}{1 + \frac{H^+}{k_a}}$$

where k_a is dissociation constant.

6.3.7 Nutrients

The nutrients can be divided into macro- and micronutrients. The macronutrients include carbon, nitrogen, phosphor, and sulfur, and an optimum ratio is 600:15:5:1. The micronutrients include iron, nickel, cobalt, selenium, molybdenum, and tungsten, which are relatively important for the growth of the microorganisms.

6.4 Types of Biogas Digesters

6.4.1 CSTR

CSTR is the acronym for the continuous stirred tank reactor, which is the most common anaerobic digestion system on the industrial scale. In CSTR, the digester contains a mixer in the middle, which rotates continuously. The produced biogas is stored and collected in a balloon or a reservoir. The mixer is usually centered vertically and rotates in a low axial speed to avoid fouling and provide enough mixing for the substrate to get in contact with the microorganisms (Al Seadi 2008).

6.4.2 UASB

UASB, the acronym for upflow anaerobic sludge blanket reactor, which is mainly used to treat wastewater and the biogas is a by-product. In this type of digesters, the feed is provided from the bottom, and it flows through the agglomerated biomasses which are mostly methanogens. The rapid contact between agglomerated biomass and wastewater results in higher rate of biogas production. Usually, the retention time varies between 6 h and 8 days, which is much shorter compared to the retention time for solid substrates and conventional biogas systems. In addition, the methane content is high from the UASB due to two reasons: (1) the dissolution of carbon dioxide at lower temperatures and (2) the produced biogas goes through the long column, where the CO_2 gets absorbed (Al Seadi 2008).

6.4.3 Plug Flow

The plug flow designs are more common in the tropical countries for the domestic biogas production. The balloon and PVC-based digesters are quite popular which are operated in the ambient conditions. In the plug flow digesters, the movement of the substrate will happen from one end to another end without mixing. Since there are no moving parts in this digester, the lifetime of this digester is considerably long. In addition, the plug flow digesters are helpful in handling fouling problems associated with biogas production (Rajendran et al. 2012).

6.4.4 Fixed Dome

There are about 30 million fixed dome digesters available in China and India, while it is the most common digesters for household and agricultural purposes. The fixed dome digesters contain three chambers including the feed tank, digester, and digestate collection pit. These digesters are usually placed beneath the ground. These digesters are not temperature controlled and can affect the biogas production during winter seasons (Rajendran et al. 2012).

6.4.5 Floating Drum

In the floating drum design, an iron or fiber drum is placed on top of the digester on the vertical axis. This allows the drum to move up and down based on the accumulation of the biogas produced. The stored biogas has enough pressure to use it for cooking application. The constraint with this digester system is that the size cannot be increased more than 50 m^3 due to the weight of the drum and some fibrous materials could block the movement of the drum. Figure 6.1 shows the schematic sketch of the different biogas digester designs (Rajendran et al. 2012).

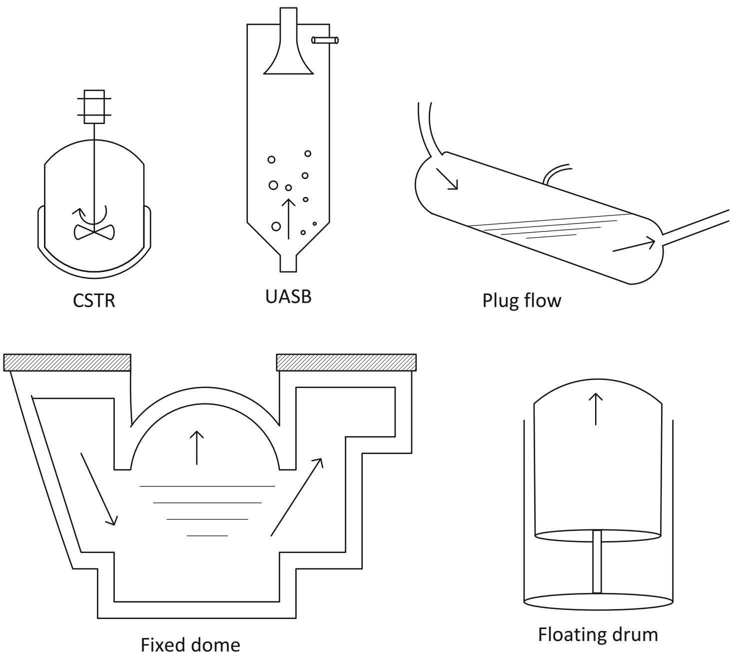

Fig. 6.1 Different biogas digester designs

6.5 Psychrophilic Digestion

6.5.1 Overview

Psychrophilic digestion takes place at temperatures less than 25 °C, and it usually happens on the domestic scale, especially during the winter season. The consequence of the psychrophilic digestion is that it increases the retention time which subsequently increases the size of the digester. The common retention time for the psychrophilic digestion is about 60–80 days. Another disadvantage with the psychrophilic digestion is that effective hydrolysis may not happen as it requires higher temperatures, and as a result, the overall efficiency of the process is reduced.

Another aspect in the psychrophilic digestion is the dissolution of carbon dioxide. In lower temperatures, the carbon dioxide is dissolved in the system leaving a high concentration of methane, which is beneficial for the application purposes. However, the dissolution of carbon dioxide results in the formation of carbonic acid which reduces the pH and thus affects the overall stability of the systems. This is the reason why most domestic biogas systems fail and the OLR cannot be increased higher than 1.5 gVS/L/day.

6.5.2 Advantages and Disadvantages

The advantage for the psychrophilic digestion is the less energy requirement, and it is much suitable for the tropical conditions or the household digesters, where the temperature effect is negligible. The digestate after treatment in psychrophilic processes contains higher TS than the thermophilic processes, which is why it is easy to handle as a fertilizer. On the other hand, the disadvantages include the treatment of harmful pathogen after treatment, before releasing to the environment. The longer retention times in psychrophilic digestion increases the total digester volume is another hassle.

6.6 Thermophilic Digestion

6.6.1 Overview

Thermophilic anaerobic digestion (50–60 °C) is an alternative to conventional mesophilic anaerobic digestion (35 °C). Thermophilic AD has been studied since the 1930s. Since the late 1980s, it was known that thermophilic AD can achieve higher efficiency and can operate under lower retention time than comparable mesophilic digestion (Willis and Schafer 2006). During this period pathogen reduction was also recognized. However, the application was hindered by the major concern of process stability and the odor formation. These concerns were dispersed in the 1990s, where the stable operation of thermophilic digestion was proved. Currently, there are still more mesophilic AD plants, but the gap between mesophilic and thermophilic plant tends to decrease.

6.6.2 Advantages and Disadvantages

Traditionally, AD plants have operated in the mesophilic temperature range, since it was difficult and costly to maintain a high temperature in the digester. However, it was recognized that thermophilic AD holds several advantages over the mesophilic. Thermophilic digesters operate at a faster rate (shorter hydraulic retention time) and with higher loading. They archive higher methane production and enhanced pathogen removal. Due to certain legislation, many feedstocks have to undergo a sanitation process at elevated temperature (i.e., 70 °C for 60 min). In these cases, since the feedstock is already heated, thermophilic digestion can be more favorable from an economic point of view. The main disadvantages are higher energy input and a higher degree of operation and monitoring. Typically, thermophilic methanogens are more sensitive to changes in operation conditions; therefore without proper control, ammonia and/or volatile fatty acid (VFA) inhibition is more likely to happen (Forgács 2012). Table 6.2 presents a detailed comparison between the conventional mesophilic and thermophilic AD.

6.7 Wet and Dry Digestion Technology

Anaerobic digesters are categorized based on their total solid (TS) content as wet ($\leq$10% TS) and dry ($\geq$15% TS). Both wet and dry anaerobic digestion processes have their advantages and disadvantages (as summarized in Table 6.3). Wet digestion systems are designed to utilize dilute organic slurries containing typically less than 15% TS which is in liquid form. Solid waste also can be used in wet AD systems; however, water addition is required to reduce the solids content. Moreover, due to a

Table 6.2 Comparison of mesophilic and thermophilic anaerobic digestion

	Mesophilic AD	Thermophilic AD
Temperature	25–45 °C	50–60 °C
Digestion period	Longer (18–60 days)	Shorter (8–18 days)
Gas production rate	Slower	Faster
Reactor volume	Bigger	Smaller
Operating cost	Cheaper	Dearer
Capital cost	Cheaper	Dearer
Pathogen kill	Lower	Higher
Toxicity problem	Less	More
Loading rate	Lower	Higher

Table 6.3 Comparison of wet and dry digestion

	Wet anaerobic digestion	Dry anaerobic digestion
Dry matter	5–10%	15–50%
Reactor design	Complete mixing	Plug flow, complete mixing
Reactor volume	Larger	Smaller
Capital cost (setup)	Higher	Cheaper
Operating cost	Dearer	Cheaper
Gas production/unit feedstock	Lower	Higher
Mass removal rate	Lower	Higher
Gas quality	Stable	Not stable
Toxicity problem	More	Less
Digestate dewatering	Expensive	Cheaper
Suitability	Ideal for slurry, wastewater, and manure	Ideal for silage, straw-based feedstock

large amount of water in the AD reactor, the system requires a large amount of energy for heating. The digestate of wet AD process has high water content and relatively low solids, and it can generate difficulties in the digestate management, for example, storage and transportation, and limits its potential application (Li et al. 2011).

Dry AD digesters are designed to operate under high TS content, typically, a thick slurry containing more than 20% TS is utilized in dry systems. Typically, the fresh feedstock is mixed with partly digested material from the digesters to accelerate the digestion process and adjust the moisture level. In other systems, leachate is recycled into the digester to speed up the anaerobic process. It is worth to mention that increasing the solid content has a limitation; several researchers reported that solid content over 30% strongly inhibits the methanogens. For handling the solid waste, most designs involve conveyor belts, screws, and powerful pumps, which are more expensive and in some cases more energy-intensive; however, heating has minimal energy requirements. Dry systems are considered to be more robust and flexible than wet systems. They are not sensitive to contaminants including glass, plastic, and grit. Dry digesters can operate higher organic loading and require smaller digesters. Moreover, management of the digestate is much easier due to its lower moister content. The digestate can be further treated by composting. It is stackable, and it can be stored in the open and in stockpiles on site; therefore there is no need for large storage tanks or lagoons for the digestate (Li et al. 2011).

6.8 Application of Biogas

As it stated in previous section, biogas is typically composed of 50–70% methane (CH_4) and 30–50% carbon dioxide (CO_2). Moreover, it usually contains impurities such as nitrogen (0–5%), oxygen (1%), hydrocarbons (1%), hydrogen sulfide (0.5%), ammonia (0.05%), water vapor (1–5%), and siloxanes (0–50 mg/m^3).

Biogas can be utilized in many ways including cooking, heat, and/or electricity production or as vehicle fuel; however, in many cases most or all part of the impurities should be removed before application (Holm-Nielsen et al. 2009).

6.8.1 Cooking

Cooking is one of the simplest applications for biogas. It is widespread in developing countries, including China and India, where biogas is typically produced in small-scale facilities. For this purpose, the biogas produced is distributed directly through a pipe from the household digester (1–3 m^3) to the kitchen, where the gas is burned for cooking on a gas stove. Biogas can be used in its raw form (cleaning or upgrading the biogas is not required). Currently, more than 30 million household operates in China. By 2020, the number of digesters is expected to exceed 80 million supplying over 300 million people with biogas for cooking propose (Rajendran et al. 2012).

6.8.2 Electricity Production

Producing electricity and heat in combined heat and power plants (CHP) is the most common utilization form of biogas in industrial countries. Electricity from biogas is considered as green electricity, and most of the European countries developed a financial support system to promote it. In a CHP unit, the biogas is converted to heat and electricity. The efficiency of the CHPs varies depending on the size; typically electrical efficiency varies around 30–40%, while thermal efficiency is around 40–50%. The requirements for the quality of the gas in a CHP unit are quite strict; however, the H_2S level should be lower than 250–500 ppm, and the siloxanes should be removed to guarantee a long operation of the CHP plant (Ryckebosch et al. 2011).

6.8.3 Vehicle Fuel

Upgraded biogas, usually referred to as biomethane, can be used as a vehicle fuel or injected directly to the natural gas grid. Several upgrading techniques exist, such as water scrubbing, pressure swing adsorption, chemical absorption, as well as cryogenic and membrane separation. During the upgrading carbon dioxide, hydrogen sulfide, ammonia, particles, and water (and sometimes other trace components) are removed to obtain a product gas with methane content above 97%. Worth to mention that, the regulation and specification of biomethane varies from country to country (Nijaguna 2006).

6.9 Economic Outlook

The economics of an AD plant varies widely depending on the location, the size of the plant, the technology used, and other factors such as the funding sources, supply chain, and market demand situation. This section presents the main economic aspects that should be considered, without any cost figures were given.

Anaerobic digestion can only be successful and economical if there is a continuous demand for its products. Therefore, the first step for identifying the optimal location is a comprehensive market demand analysis. This analysis should include the following aspects:

- Identification of market size and ideal form of the products (i.e., electricity, heat, biomethane, etc.).
- Identification of all possible customers for biogas and/or digestate.
- What is the customers' willingness and ability to pay?
- Which other factors influence the sales of products from AD?
- Current regulation and legislation which can affect the business.

The market demand analysis is typically followed by a cost-benefit analysis, which evaluates that implementation of the AD system is sustainable or not. This analysis includes all cost related to an AD installation as well all the predicted revenues (Rajendran et al. 2014).

6.9.1 Investment Costs [Also Called Capital Expenditures (CAPEX)]

The investment cost depends on several factors such as:

- Size and technology of the AD system
- Land space required and costs of land acquisition
- Planning studies and required surveys
- Civil works at the facility including support structures and buildings
- Construction of the digester
- Biogas pipes
- Large and small mechanical equipment (e.g., shredder)
- Transport of materials (including insurance)
- Customs duties, taxes

6.9.2 Operational Costs [Also Called Operational Expenditures (OPEX)]

Operation costs include all costs associated with the operation of the service and maintenance of the system. At a household level, operational costs are negligible, because waste material is used as feedstock and the operation of the digester mostly carried out by family members. For industrial biogas plants, operation cost includes insurance, electricity, water, transport of feedstock, spare parts, staff salaries, etc.

6.9.3 Revenue

The major sources of income from anaerobic digestion come from the sale of biogas and digester-related products; however, in many cases, the AD plants have other income sources as well. The most common revenues are:

- Sales of biogas (or a product from its processing such as heat and electricity)
- Sales of digestate as fertilizer
- Income from financial support system (e.g., renewables obligation certificates, feed tariffs)
- Gate fees

6.10 Conclusion

This chapter summarizes the different technologies used in anaerobic digestion specific to the purpose of extremophiles, i.e., psychrophilic and thermophilic AD technologies. Furthermore, the important process parameters in AD processes were discussed on how it will affect both psychrophilic and thermophilic digestion. Later, the technologies on wet and dry digestion were compared on the different solid loading levels and its importance in the handling of digestate and how it can reduce the overall volume of the digester. The briefings on economic outlook suggest the important factors, which should be considered when designing a biogas plant.

Take-Home Message

- The choice of the digester type used depends on the substrates, cost, and location of the plant.
- Thermophilic digestion technology produces more biogas compared with psychrophilic digestion.
- Profitability of the biogas plant is influenced by the purity of raw material/waste obtained and the type of product produced.
- Dry digestion technology is preferred over wet digestion due to the easiness of handling digestate after digestion.
- Financial support/Incentivization system plays a crucial role in the profitability of anaerobic digestion.

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