Chapter 8
Bioprocess Parameters for Thermophilic and Mesophilic Biogas Production: Recent Trends and Challenges

Rahul Kumar, Uttam Kumar Neerudu, Ragini Gothalwal, Swati Mohapatra, Pallav Kauhsik Deshpande, M. Mukunda Vani, and Ramchander Merugu

Abstract The latest advancements in technology have led to the progress in designing more efficient anaerobic digestion (AD) systems which have incorporated modifications such as feedstock pretreatment methods, bioprocess improvements, techno-economic gas upgrading, and superior digester designs among others. The different types of feedstocks being used, the mechanism of biogas production, the operation of a biogas plant, and the different types of digesters used for anaerobic digestion are explained. The various process parameters like pH, temperature, electrical conductivity, etc. are also discussed. Challenges in anaerobic digestion along with the advantages and disadvantages of biogas generation are deliberated. Further, the microbial population involved in various stages of process is presented. In this chapter, the existing state of biogas technology highlights the latest advancements in its applications as well as production.

Keywords Biogas · Anaerobic digestion · Feedstock · Mechanism · Process parameters

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R. Kumar
Department of Environmental Sciences, H.N.B. Garhwal University (A Central University), Srinagar, Uttarakhand, India

U. K. Neerudu
Department of Biochemistry, Mahatma Gandhi University, Nalgonda, Telangana, India

R. Gothalwal · P. K. Deshpande
Department of Biotechnology, Barkatullah University, Bhopal, Madhya Pradesh, India

S. Mohapatra
Amity Institute of Microbial Technology (AIMT), Amity University, Noida, Uttar Pradesh, India

M. M. Vani
Department of Chemical Engineering, Anurag University, Hyderabad, Telangana, India

R. Merugu (✉)
Department of Biochemistry, Mahatma Gandhi University, Nalgonda, Telangana, India

Department of Biotechnology, Barkatullah University, Bhopal, Madhya Pradesh, India

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8.1 Introduction

The continuing use of fossil fuels is responsible for many ecological concerns. This necessitated a shift to focus from fossil fuels to more sustainable biofuels. Fossil fuels are depleting and are responsible for environmental pollution. Moreover, about 88% of present-day energy requirements are being met by fossil fuels. As they are depleting, research efforts are initiated for alternative fuels which are sustainable and environment friendly (IEA 2015). Kothari et al. (2010) opined that biogas is best suited for tropical climates as an environmental friendly and can aid in sustainable development. It can be used for heart generation and electricity generation. It can provide source of fuel to the rural population where there is less access to electric power. It can be used as a substitute to firewood and charcoal. Anaerobic digestion is a procedure where many diverse microbes transform organic waste to biogas. These microorganisms can survive in anaerobic environments where the transformation of organic matter to biofuel will take place. Wetlands generally are the most commonly found areas where the presence of these microorganisms will be seen. Apart from these freshwater sediments, digestive tracts of animals also host such environments for the growth of the microorganism. This process is exploited for the production of biogas using similar conditions where the necessary conditions for the growth of anaerobic bacteria like pH, temperature, and anoxic conditions are maintained. A part from this process is also used for the preparation of biofertilizers from agriculture and domestic waste. Anaerobic digestion is used for waste treatment and biogas production (De Baere et al. 2010). It is a sequence of biological techniques that use a different kind of bacteria to break down organic matter into biogas, mainly methane and mixture of different gases (like carbon dioxide, hydrogen in anoxygenic conditions) (Antoni et al. 2007). A biogas unit consists of reception tank, digester, gas holder, and an overflow tank. The improvement of reactor for anaerobic digestion generation has undergone further advancements over the years. Ribas et al. (2009) reported 70% COD elimination along with 70% methane content in biogas with the aid of a mesophilic SBBR reactor while treating sugar cane-vinasse. Almeida et al. (2017) studied configuration of different types of reactors. He observed that the removal efficiency of COD increased by 97%. The effect of physicochemical parameters on the biogas plant efficiency was also reported (Chen et al. 2017; Hong and Haiyun 2010; Hussain et al. 2017; Liu et al. 2016). A thermophilic digester functions at temperatures more than 50 °C generating biogas. It has some benefits such as that it does not need agitation and is quicker in fermentation than a mesophilic digester. Vinasse produced at more than 70 °C can be used for this kind of biodigester. The main types of biogas production plants are fixed-dome plant and floating-drum plants. In fixed dome type, the digester is fixed with a gas holder. The costs incurred in operation are quite low, and the life span of these kinds of digesters is generally about 20 years.

In conventional systems the major limitations are high space requirement, low OLR/high HRT, low treatment efficiency, and biomass washout. Anaerobic digestion can be classified into two types, namely, wet digestion and dry digestion based on solid content present. Later an even more effective technology came into being combining both the modes called co-digestion. Wet anaerobic digestion systems are used to treat sewage water and industrial effluents which contain low amounts of solids. In dry digestion, high solid content substrates (25–40%) are treated (Verma 2002). Heat and nutrient transfer is good in wet processes when compared to dry processes (Luning et al. 2003; Wellinger et al. 1993). In the process of dry digestion, municipal solid waste (MSW) and energy crop residue digestion are generally done. These systems could reach higher organic loading rate values resulting in smaller volumes of digestate and hence are more economical when compared to wet digestion processes. Co-digestion is the process of transformation of various feedstocks. In contrast to conventional methodology used for anaerobic digestion process, mixtures of substrates are used as feedstock. Of late, this procedure was adopted by many countries. Mathias (2014) proposed the use of four types of anaerobic digesters, namely, "continuously stirred tank reactors (CSTR); upflow anaerobic sludge blanket (UASB) reactors, upflow anaerobic filter (UAF) digesters, and baffled digesters." The digester to be used in the process is dependent on the major type of the substrate which would be treated in the process. Substrates with more amounts of total solids are treated in continuously stirred tank reactors (CSTRs). Other types of feedstocks especially dissolved organic solids are treated in upflow anaerobic sludge blanket (UASB) reactors, anaerobic filters, and fluidized bed reactors (Mathias 2014). The process takes place in a single step in which the substrates are digested till we reach a solid dry content between 8% and 15%. According to Langeveld et al. (2016), the major advantages of co-digestion when compared to other types of digestion strategies are enhanced biogas yields and lower emission of greenhouse gases, process stability, homogenization, high nutrient recycling, and continuous production of biogas in all season.

The feedstocks are treated at very high temperatures for hydrolysis of substrate to make it more homogeneous. Figure 8.1 shows the conversion of food waste to biogas and the intermediate steps involved in it. It also removes contaminants present in the feedstock and to produce a uniform biomass. The refined organic substances are treated at high temperatures to enhance biogas generation. This process also helps in the pasteurization of the waste. The process generally involving treatment at temperatures about 70 °C with hydraulic retention time (HRT) of 1 h is done to pasteurize the waste as required by national and international regulations. The slurry obtained after pasteurization is cooled. The temperature should be equal to that of the digester operating temperature. Using a heat recovery system, the excess heat is recovered. It will be then used to treat the unpasteurized organic waste. Pathogenic microorganisms are eliminated through the process of thermal treatment. Thermal treatment of high lignocellulosic contents will result in higher organic transformation efficiencies especially when the organic waste is heated up to 165–170 °C for half an hour. In anaerobic contact process, the limitations are high space requirement and not suitable for high organic rate loading. Moreover, no phase separation takes place, and the tank must be always closed to prevent foul smell. In case of fluidized bed reactor (FBR), difficulties in maintaining optimum mixing and difficult to start-up conditions are seen. It would also be difficult to scale up the

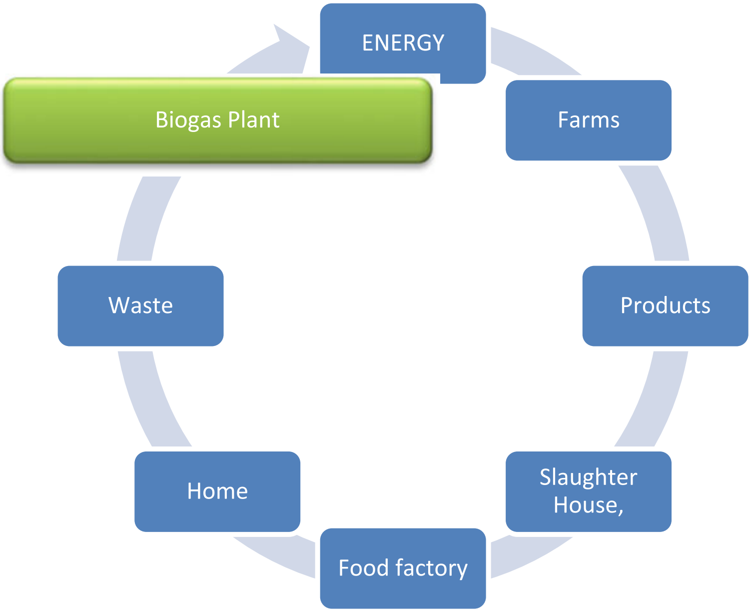

Fig. 8.1 Conversion of food waste to biogas

process to industrial scale. In case of upflow anaerobic sludge blanket (UASB), the disadvantages of operation are that performance is based on the granule formation which in turn depends on the type of wastewater being used and phase separation does not take place. The process of start-up will be delayed if suitable innoculum is not selected. In anaerobic baffled reactor (ABR), variable system hydraulics difficulties and biomass growth are seen. Expanded granular sludge blanket (EGSB) is energy intensive, has poor process stability, is the absence of phase separation, and is not appropriate for wastewaters containing more solid contents. In anaerobic filters, the major disadvantages are no phase separation takes place, problems with mixing, not appropriate for wastewaters with solid contents, and high energy requirement (Akunna 2018). Wet fermentation systems are those in which only 15–25% solids are present. System in which more than 30% high solids are present is called dry fermentation. The slurry is digested in wet fermentation. Many digesters comprise a single reactor vessel but can be divided into two stages with more than one reactor vessel. Hayes et al. (1979) observed that plug-drift digesters use slurries. Bruins (1984) has reported that at low concentration of total solids, problems with floating and settling layers are seen and suggested that this can be overcome by vertical mixing inside the pipe. During this process, the phenomenon of hydrolysis and that of methanogenesis is separated in the pipe. Hydrolysis occurs first followed by methanogenesis. In this type of system, the SRT is the same as that of HRT.

8.2 Thermophilic and Mesophilic Anaerobic Digestion

Thermophilic anaerobic digestion will take place at temperatures above 50 °C. The biggest advantage of thermophilic digestion is the decrease in retention time which could be as low as 10 days when compared to mesophilic reactors where the retention time is about 20 days. The advantages are that mixing energy requirements are less and overall heat loss per unit volume of material processed also is less apart from pathogen reduction. In the third process, hydrolysis stage is the rate-limiting step. This is overcome in the thermophilic digester which operates at high temperature range so that hydrolysis takes place efficiently. Thermophilic anaerobic digestion generated higher amounts of biogas production. The disadvantage is that there tends to be accumulation of volatile fatty acids which decrease the biogas yield. The thermophilic anaerobic digestion process is also instable. Other limitations are that the water quality gets worse, fluctuation in temperatures, and sensitivity to toxic heavy metals (Khemkhao et al. 2012). The process is energy intensive as more energy is required for raising the initial temperature. The anaerobic process which operates at mesophilic temperature range (35–38 degree centigrade) is called mesophilic digestion. This temperature range can produce class A biosolids. Thermophilic digesters need lesser time to process feedstocks but are difficult to operate and are expensive. Kushkevych et al. (2020) have investigated the diversity of various thermophiles which are occurring in mesophilic biogas plants located in Czech Republic. They found 19 thermophilic genera using 16S rRNA gene sequencing. Most of the thermophilic population was found in substrate containing primary sludge and biological sludge, and less were found in maize silage and liquid pig manure. Bolzonella et al. (2020) have treated agrowaste using a thermophilic post-hydrolysis process in a digester operated for 3 days to increase the production of biogas by 30%. Dai et al. (2020) have proposed a thermophilic mixed culture fermentation (TMCF) for enhancing the production of methane and hydrogen with a high substrate degradation rate and low gas solubility. Lei et al. (2020) have investigated thermophilic anaerobic digestion (TAD) of *Arundo donax*, an energy crop with high cold tolerance to understand the relation among microbial population and their functions during the process of fermentation. They have observed *Firmicutes* with three dominant genera of *Tepidiphilus*, *Sedimentibacter*, and *Gelria* during the thermophilic anaerobic digestion process apart from *Methanoculleus* and *Methanosarcina*. Wu et al. (2020) compared the process of anaerobic digestion of municipal sludge with high (10%) solid content under both mesophilic and thermophilic conditions. Thermophilic digestion was better than mesophilic anaerobic digestion for biogas production. Mesophilic anaerobic digestion showed more microbial diversity than thermophilic anaerobic digestion.

Ryue et al. (2020) reviewed the usual and promising methods for improving process stability in thermophilic anaerobic digestion. Zhang et al. (2020) used a mixing strategy for treating food waste and chicken manure under thermophilic conditions using a mesophilic innoculum. They observed that methane yield in the continuous stirred reactor was 71.3% more when compared to intermittent agitated reactor. Hirota (2020) investigated production of methane in wet and semi-dry anaerobic digesters. Maximum levels of methane gas were seen for 30 days in both thermophilic conditions. In anaerobic digestion, new studies of using hyper-mesophilic temperatures were reported by Moestedt et al. (2014). The range of organic loading rate is 3–5 kg VS/m^3/d. Hyper-mesophilic temperatures between 40 and 44 °C have been explored for different kinds of substrates (Westerholm et al. 2015). van Lier et al. (1993) and Lindorfer et al. (2008) have earlier observed process instability when hyper-mesophilic conditions were used for anaerobic digestion process for mesophilic microorganism. However, Moestedt (2015) has reported higher biogas yield in digestion of food and slaughterhouse waste in Linköping biogas plant. Biogas produced during the process of anaerobic digestion are made up of material such as PVC-coated fiber fabric, etc.. Labtut et al. (2014) have done a comparative study between mesophilic and thermophilic processes and concluded that a mesophilic digester was stable regardless of the organic and influent composition, while thermophilic digester performed better at high organic loading rates. They have also observed that the stability of thermophilic digester was dependent on influent composition when compared to mesophilic digester. Performing anaerobic co-digestion of food waste with lignocellulosic wastes can overcome the limitations of their respective mono-digestions. Mahdy et al. (2020) evaluated the influence of hyper-thermophilic pre-hydrolysis stage on methane recovery using sewage sludge and microbial populations present in them. Bacteroidetes and Cloacimonetes populations were more, while there was reduction in the population of Firmicutes. Prem et al. (2020) studied the microbial community dynamics when proteinaceous wastes were treated in mesophilic and thermophilic batch reactors. They have observed that in mesophilic samples, acetoclastic methanogenesis took place where phenylacetate (PAA) levels favored the growth of *Psychrobacter* spp., while phenylpropionate (PPA) favored the growth of *Haloimpatiens* spp. Lopez et al. (2020) assessed the microbial quality of sewage sludge which was treated in three different plants: two anaerobic and one aerobic plant. Out of the three, one was anaerobic mesophilic, one was anaerobic thermophilic, and the last plant was aerobic thermophilic. They have observed that anaerobic thermophilic treatment could decrease the concentration of the *Enterococcus* sp., while aerobic thermophilic could decrease the concentrations of *E. coli*.

8.3 Mechanism of Biogas Production

The groups of microbes involved in anaerobic digestion are poorly understood. Angelidaki et al. (2011) have reported that the bacterial communities involved in anaerobic digestion can be divided into fermenting bacteria, anaerobic bacteria, and methanogens. The oxidizing microorganisms oxidize these reduced substances to hydrogen, formate, acetate, and carbon dioxide (Angelidaki et al. 2011). Propionate accumulation is seen in cases of process imbalance (Angelidaki et al. 2006). Wang et al. (2012) have reported that ratio of 1.25 between propionate and acetate may lead to failure of biomethanation process. Clostridium and Megasphaera species have been reported to convert lactic acid to propionic acid (Prabhu et al. 2012; Tracy et al. 2012). Biogas has lower emission rates compared to that of any other fossil fuel, subsequently leading to less environmental pollution (Vijay et al. 2006). The need for international sustainable waste management has resulted in renewed research interest in agro-waste and biowaste-based biofuels (Weiland et al. 2009; Deublein and Steinhauser 2008). Boe et al. (2012) reported that the feedstock composition with excessive lipid or protein content shows high correlation with foam formation during anaerobic digestion. Other parameters, like temperature, digester design, and form of the mixing, are responsible for foam formation (Barber 2005). Foaming may cause blockage of mixing systems due to the presence of solids in the foam (Ganidi et al. 2009). Excess financial costs are incurred due to foaming (Barjenbruch et al. 2000). In anaerobic digestion method, four processes are involved (Bharathiraja et al. 2014), namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the hydrolysis step, carbohydrates, proteins, and lipids are hydrolyzed to single chain monomers and dimers like sugars, amino acids, and fatty acids. In step 2 (acidogenesis), the monomers and dimers from hydrolysis are turned into propionic acid, butyric acids, and valeric acids. In the case of step 3 (acetogenesis), acetic acid, hydrogen, and carbon dioxide are formed. In the last stage (methanogenesis), acetate is converted into methane and CO_2; whole hydrogen is used up. Methanogenic microorganisms are sensitive to oxygen and are less versatile when it comes to substrate utilization. Methane is generated through acetoclastic methanogenesis using acetate. Hydrogen produced will be the remaining 1/3 of the total biogas produced. Belay et al. (1986) and Lovely and Klug (1983) have observed methane production from substrates such as formate methanol and methylamines. Wolfe (2011) reported that methanogens need a higher pH at later stages of the process compared to initial stages. Richards et al. (2016) reported that *Methanococcus maripaludis* has a doubling time of just 2 h. Research by De Vrieze et al. (2012) found that *Methanosarcina* spp. is a more robust methanogen when compared to other methanogenic populations which are involved in methanogenesis. They have reported that it is capable of variations in pH and also concentrations of acetate, ammonia, and sodium. Dhamodharan et al. (2015) and Li et al. (2015) have developed many kinetic models to describe the processes involved in anaerobic digestion.

Anaerobic digestion takes place in three stages, that is, hydrolysis, acidification, and methane formation. The acidogens produce hydrolytic enzymes and transform soluble organics to volatile fatty acids and alcohols. Breakdown of carbohydrates, proteins, and lipids into sugars, amino acids, and fatty acids takes place in hydrolysis. This is carried out by specific enzymes of hydrolytic bacteria. In the hydrolysis stage, these microorganisms were observed, namely, *Peptococcus*, *Ruminococcus*, *Eubacterium*, *Bacillus*, *Butyrivibrio*, *Proteus vulgaris*, *Micrococcus*, *Staphylococcus*, *Acetovibrio*, *Clostridium*, *Lactobacillus*, *Streptococcus*, etc. The monomers released during hydrolysis are converted by fermentative bacteria into carbon dioxide, pyruvate, hydrogen or formate, ammonia, volatile fatty acids, lactic acid, and alcohols. In acetogenesis, some compounds generated during acidogenesis are oxidized to carbon dioxide, hydrogen, and acetic acid by metabolic action of acetogens. Volatile fatty acids and alcohols are then transformed by acetogenic bacteria into acetic acid, hydrogen, and carbon dioxide. During acidogenesis, *Desulfovibrio*, *Lactobacillus*, *Butyrivibrio*, *Bacillus*, *Desulfuromonas*, *Pelobacter*, *Sarcina*, *Staphylococcus*, *Selenomonas*, *Pseudomonas*, *Streptococcus*, *Clostridium*, *Eubacterium*, *Desulfobacter*, *Veillonella*, etc. are seen. In the stage of acetogenesis, *Syntrophomonas buswelii*, *Clostridium*, *Methanobacillus omelionskii*, *Syntrophomonas wolfei*, *Syntrophomonas wolinii*, etc. are involved. Methanogenesis leads to the formation of CH_4. Seventy percent of methane produced is from acetic acid by acetoclastic methanogenic bacteria. During methanogenesis, *Methanosarcina* and *Methanosaeta* were generally observed. Hydrogenophilic methanogens such as *Methanoplanus*, *Methanobacterium*, *Methanospirillium*, *Methanobrevibacter*, etc. are also seen (Wheatley 1991; Stronach et al. 1986). Methanogenic bacteria then use acetic acid or hydrogen and carbon dioxide to generate methane. Yang et al. (2004) have reported that the yield of biomethane is never greater than 60% of theoretical yield. The possible reason for this decrease is the presence of other compounds which do not undergo degradation and are resistant such as lignin, cellulose, or some complex proteins in the waste:

$4CH_3COOH \rightarrow 4CH_4 + 4CO_2$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

$4CH_3OH \rightarrow 3CH_4 + CO2 + 2H_2O$

$CH_3OH + H_2 \rightarrow CH_4 + H_2O$

8.4 Microorganisms in Anaerobic Digestion

Different groups of bacteria such as *Methanoculleus bourgensis*, *Peptoniphilus sp.*, *Ruminiclostridium cellulosi*, *Herbinix hemicellulosilytica*, *Clostridium bornimense*, and *Clostridium ultunense* participate in various anaerobic digestion stages (Mauset al. 2014, 2016; Hahnke et al. 2014; Koeck et al. 2015; Tomazetto et al. 2016; Manzoor et al. 2013; Sun and Schnürer 2016). *Methanoculleus* species are known to be one of the most biologically involved organisms in methanogenesis (Nettmann et al. 2010; Wirth et al. 2012; Maset al. 2014). *M. bourgensis* is an important microbial species in the process. Certain genes involved in methanogenesis and osmolytes production were found in the *M. bourgensis* MS2T, and much of the genetic information commonly seen in methanogenesis in biogas plants was found in its genome (Maus et al. 2016). Hahnke et al. (2015) used the Illumina MiSeq system to sequence the anaerobic *Porphyromonadaceae* bacterium, which was isolated from an anaerobic digestion plant. They suggested that the bacterium may play a role in both hydrolysis and acidogenesis stages, as its genome showed the presence of genes which can produce proteins capable of breakdown of complex carbohydrates and production of fatty acids (VFAs). Koeck et al. (2014) sequenced *Ruminiclostridium cellulosi* DG5, a thermophilic, anaerobic, and cellulolytic bacterium which was responsible for lignocellulose degradation. The enzymes included mainly belong to hydrolase group that are most engaged in hydrolysis and regenerating glycosidic bonds. *Herbinix hemicellulosilytica* was isolated from a thermophilic biogas reaction and was capable of breaking down cellulose at higher temperatures (Koeck et al. 2015).

High-performance genomics and metagenomics sequences are used to investigate the bacteria present in the biogas generation. In order to improve the biogas digestive function, the presence of highly efficient microbial communities, hydrolyzing polymers varying from methane, is essential. Further understanding has limitations as a large part of biodiversity is unaffected (Tian et al. 2016). Thus, the identification and designation of microbial pathways of biogas production is an important function (Stark et al. 2014). NSG strategies and "omics" have significantly reduced costs and improved the reliability and consistency of the sequence data generated. These benefits make it possible for tens of amplicon samples immediately after hundreds of amplicon samples for a single operation without the need for the initiation and cultivation of individual microorganisms (Vanwonterghem et al. 2014; Delmont et al. 2012). Different metagenomics techniques, such as denaturing/Moche gradient gel electrophoresis (Connaughton et al. 2006; Liu et al. 2009a, b), terminal restriction fragment length polymorphism (T-RFLP) (Carballa et al. 2011; Ziganshin et al. 2013), sequence (Dong et al. 2015), fluorescence in situ hybridization (FISH) (Nettmann et al. 2010), and p4osequing (Li et al. 2013), were used for studying microbial populations in biogas digestion. These studies have been done on large microbial communities, lab small (Li et al. 2013), and small-scale reactors (Dong et al. 2015; Tian et al. 2016). Hassa et al. (2020) have analyzed the genome sequence of *Methanothermobacter wolfeii* SIV6 isolated from a thermophilic industrial-scale biogas fermenter and reported an operon encoding different subunits of the enzyme methyl-coenzyme M reductase which catalyzes the rate-limiting step during methanogenesis. The different kinds of microbes isolated from biogas treatment plants are tabulated in Table 8.1.

Table 8.1 Microorganisms isolated from biogas treatment plants

Name of the organism	Type of feedstock	References
Methanoculleus bourgensis	Sewage sludge	Maus et al. (2015)
Porphyromonadaceae	Maize silage; pig and cattle manure	Hahnke et al. (2015)
Clostridium bornimense M2/40	Maize silage and wheat straw	Hahnke et al. (2015)
Ruminiclostridium cellulosi DG5	Cellulolytic biogas plant	Koeck et al. (2014)
Peptoniphilus sp.	Maize silage	Tomazetto et al. (2014)
Clostridium Bornimense M2/40T	Maize silage and wheat straw	Tomazetto et al. (2016)
Clostridium ultunense	Acetate-oxidizing sludge	Manzoor et al. (2013)
Clostridium sp.	Slaughterhouse waste	Sun and Schnürer (2016)

8.5 Process Parameters Affecting Anaerobic Digestion

The anaerobic digestion operation depends on the temperature which is one of the primary factors which affects the production of biomethane. Other factors which are important in the process are pH, alkalinity, and toxicity. At the temperatures range of 35–37 °C Lettinga and Haandel (1993). Mesophilic organism's growth will take place. Anaerobic digestion occurs at three different kinds of temperature which are psychrophilic (10–20 °C) conditions, mesophilic (20–40 °C) conditions, and thermophilic (50–60 °C) conditions. Based on the growth rate of the bacteria at these temperatures, retention time of the process differs. Since the growth of bacteria is slower at lower temperatures, a longer retention time is required for psychrophilic anaerobic digestion when compared to mesophilic or thermophilic digestion. The local construction regulations of the place where the digester is being built has to be kept in mind. Different kinds of pretreatment methods are show in Table 8.2.

The following parameters are generally used for process design and operational control during anaerobic digestion.

1. Hydraulic Retention Time (HRT).
   $\text{HRT} = \text{Volume of Aeration Tank (V)/Influent flow rate (Q)}$.
2. Organic Loading Rate (OLR).
   $\text{OLR} = Q \times So/V$.
3. Solids Retention Time (SRT).
   $\Theta c = VX / (Q\text{-}Qw)\ Xe + Qw\ Xw$
4. Hydraulic loading rate (HLR).
   $\text{HLR} = Q/A$
5. Specific biogas yield.
   $\text{Ybiogas} = \text{Qbiogas} / Q(So\text{-}Se)$

Table 8.2 Anaerobic digestion pretreatment methods

Pretreatment	Feedstock	References
Physical	Straw	Motte et al. (2014)
	Fruit and vegetable waste three sonication times of 9, 18, and 27 min, operating at 20 kHz	Zeynali et al. (2017)
	Olive mill solid residue	Rincón et al. (2013)
Chemical	Cotton stalk residues	Zhang et al. (2018)
	Agriculture straw	Song et al. (2014)
	Sunflower oil cake	Monlau et al. (2013)
Biological	Food waste	Lim and Wang (2013)
	Chicken feathers	Patinvoh et al. (2016a)
	Paddy straw	Phutela and Sahini (2012)
	Organic waste	Wagner et al. (2013)
Thermal	Wheat straw	Rajput et al. (2018)
	Hay	Bauer et al. (2014)

6. Specific biogas production rate (BPR).
   BPR= Qbiogas/V
7. Treatment efficiency.
   % COD removal = So-Se/So X 100

Even the reactor volumes have to be larger for the psychrophilic digestion. If the pH values are between 6.5 and 7.5, the rate of production of biomethane will be less. Hence, hydrogen carbonate is added to the reactor to maintain optimum pH for higher methane generation. Numerous compounds such as volatile fatty acids, ammonia, sodium, calcium, heavy metals, sulfide, and xenobiotics have a detrimental effect on the production of the methane. Anaerobic digestion involves a diverse group of microbes such as methanogens which are sensitive to cultural conditions under which they grow. Hence, the cultural conditions have to be optimized to see that the maximum production of biogas takes place. Secondly, some organic as well as inorganic compounds present in the substrate can be toxic to the entire process of anaerobic digestion (Boe et al. 2012). The factors that affect biogas production are as follows:

(a) pH

   pH plays a major role in anaerobic digestion. As the process is divided into different stages, pH at various stages has to be maintained differently so that the microbial growth at different stage is not inhibited. During the hydrolysis stage, the pH should be maintained between 5.0 and 6.0, while the pH required during the phase of acidogenesis stage is between 5.5 and 6.5. In the stage where the actual production of methane takes place which is called methanogenesis, the pH required is about 6.8–7.2. When the pH is not optimized as required, volatile fatty acids will be generated. The presence of these will inhibit the growth of the methanogenic microorganism. Changes in volatile fatty acid (VFA) levels are always measured as it is a good indication of the stability of the operation. The concentration of the volatile fatty acids (VFAs) will change based on process parameters like HRT, OR, or temperature.

(b) Temperature

   A constant process temperature is essential for a successful anaerobic digestion process (Jain and Kalamdhad 2018). Increased temperature leads to increased metabolism and an increase in nutrient requirement. The various performance enhancers are explained by Carlsson et al. (2012). The different approaches being used are seeding, particle size reduction, ultrasonic pretreatment, addition of metals, thermal pretreatment, and alkali pretreatment. Chen et al. (2017) have proposed that temperature is a vital parameter that could influence the work of an anaerobic digester. Digester working in thermophilic condition is reported to have the fastest reaction rates compared to other operating conditions, thus leading to more generation of biogas (Mao et al. 2015). However, the disadvantage of operating in such high temperatures is that inhibition of the process may take place due to increase in production of ammonia which is toxic to other groups of microorganisms (Weiland et al. 2009). Martinez-Sosa et al. (2011) and Smith et al. (2013) have also observed lower methane production under psychrophilic conditions. Fouling smell was also increased when the temperature of the digester was lowered (Gao et al. 2014). Microbial growth depends on the temperature being maintained at various stages of the process in the digester. Ennouri et al. (2016) treated urban and industrial sludge samples and found that treatment at temperature of about 120 °C leads to higher biogas formation. Bowen et al. (2014) reported those temperatures less than the optimal required led to lower substrate utilization which indirectly affects the digestion process. Kundu et al. (2014) confirmed that increase in process temperatures is associated with lower negative effects compared to lower temperatures. Similarly, Westerholm et al. (2017) have also reported that increased temperatures are beneficial for the bioprocess to take place while studying thermophilic-to-mesophilic temperature adaptation. During the process of scale up, it would be difficult to control the temperature at the required level as the ratio between surface area and volume of the digester will be decreased. Heat exchangers like cooling coil, cooling baffles, vessel wall, and external loop are generally used for controlling excess heat so as to control the temperature. Stanton number describes the ratio between "heat transfer capacity through coils and convection capacity in cooling water." This is very useful for designing a heat exchanger. The various devices which are used for temperature monitoring are bimetal thermometers, liquid thermometers, thermistors, crystal window tape, infrared detectors, etc. Clemens (2006) suggested that for maintaining temperature in biogas digesters, temperature control devices have to be used. Matsakas et al. (2020) evaluated a novel pretreatment method for enhancing methane production using hybrid system of organosolv-steam explosion fractionation. The approach was used for obtaining pretreated solid which is highly digestible from birch and spruce woodchips.

(c) Feedstock.

The non-lignocellulosic liquid feedstock which is generally used for anaerobic digestion process is palm oil mill effluent (Sri Rahayu et al. 2015). Guardia-Puebla et al. (2014) treated coffee wastewater and reported methane gas production of about 61%. They have also studied the influence of OLR and HRT in the treatment of coffee wet wastewater in a UASB reactor. Chicken feather was pretreated and was found to be effective as 75% of the feather was transformed into protein after 8 days (Patinvoh et al. 2016b). Janke et al. (2015) used vinasse as a feedstock, but lower yields of biogas were found. They suggested a reactor design with higher OLR and lower HRT. Pig and cattle manure were used as feedstock for the production of biogas (Matulaitis et al. 2015). The process showed that pig liquid manure gave more biogas yields compared to pig solid manure and cattle manure. The solid feedstock for anaerobic treatment includes food residues (Yong et al. 2015). Zhang et al. (2007) has suggested that lignocellulosic wastes are abundant renewable organic resources with 200 billion tons production every year. Kang et al. (2014) opined that the abundant lignocellulosic wastes found in nature make them a good feedstock for biogas production and can add approximately 1500 MJ/year of energy. Although they are difficult to be digested (Himmel and Picataggio 2009). The lignocellulosic feedstock which was used for anaerobic digestion was silage maize (Mumme et al. 2011). Cadavid-Rodríguez and Bolaños-Valencia (2016) used grass silage for anaerobic digestion and found that maximum methane was seen when the total solids were at 4% composition. Liew et al. (2012) studied the use of wheat straw, corn stover, yard waste, and leaves for biomethane production through anaerobic digestion and found that corn stover was the best feedstock for generation of methane followed by wheat straw, leaves, and yard waste. Sugarcane bagasse was treated with alkali to remove lignin which improved the rate of lignin removal. The maximum methane yields were found to be about 221.8 mL/g-VS (Kumari and Das 2015). Battista et al. (2016) used the lignocellulosic materials in coffee wastes by pretreating them with sodium hydroxide and observed a higher biogas production with pretreated coffee waste. Forestry residues were also used as feedstock for biogas production by pretreatment (Teghammar et al. 2014). Oil palm fiber from a Colombian palm oil mill was studied for generation of biogas (Garcia-Nunez et al. 2016a). Different types of agricultural residues from maize, coffee, cotton, sugarcane, and bananas were found to be suitable as feedstock for biogas production in Kenya (Santa-Maria et al. 2013; Nzila et al. 2017). Co-digestion of food waste and straw at 35 °C was studied by Yong et al. (2015). Brown and Li (2013) and Xu and Li (2012) have reported that co-digestion of food waste and lignocellulosic wastes helps maintain a carbon/nitrogen ratio, reduction of the start-up time, and volatile fatty acid accumulation thereby improving the overall biomethane production. Lott et al. (2020) produced high purity methane by adding H_2 and CO_2 through the process known as ex situ biogas upgrading in which agro-municipal residues such as cow manure (CM) and the organic fraction of solid municipal waste (OFSMW) were used. Agata et al. have used mild thermal pretreatment of kitchen waste and concluded it was helpful in the solubilization of macromolecules and proposed it as a promising option for enhancing biogas production. Rasapoor et al. (2020) reviewed the challenges involved in improving biogas generation and suggested balancing the waste composition, optimizing nutrient, and using additives like biochar, carbon, and phenazine for direct interspecies electron transfer (DIET). Lim et al. (2020a) studied the influence of seed sludge on microbial diversity and performance of thermophilic digestion of food waste. Lim et al. (2020b) proposed the use of biochar for overcoming process instability during start-up of the anaerobic digestion process. They observed that biochar addition enhanced the methane production by 18%. When biochar was added, the growth of electroactive *Clostridia* and other electroactive bacteria was seen, while in its absence, biochar promoted the growth of *Clostridia* and syntrophic acetate oxidizing bacteria. The types of feedstocks are shown in Table 8.3.

Table 8.3 Types of feedstocks used for anaerobic digestion process

Name of the feedstock	Reference
Palm oil mill effluent	Langeveld et al. (2014), Sri Rahayu et al. (2015)
Slaughter waste	Patinvoh et al. (2016b)
Vinasse	Janke et al. (2015)
Potato effluent	Hung et al. (2006), Verheijen et al. (1996)
Coffee wastewater	Segura-Campos et al. (2014)
Pig slurry	Matulaitis et al. (2015)
Wheat straw	Liew et al. (2012)
Sugarcane bagasse	Kumari and Das (2015)
Coffee parchment	Battista et al. (2016), Syarief et al. (2012)
Oil palm fiber	Garcia-Nunez et al. (2016b)
Banana flower stalks	Santa-Maria et al. (2013), Nzila et al. (2015)
Grass silage	Cadavid-Rodríguez and Bolaños-Valencia (2016)
Corn Stover	Liew et al. (2012) and Li et al. (2011)
Coffee pulp	Battista et al. (2016) and Syarief et al. (2012)
Forestry residues	Hoyne and Thomas (2001)
Fruit bunches	Garcia-Nunez et al. (2016b), Zhang et al. (2012)
Banana leaves	Santa-Maria et al. (2013), Nzila et al. (2015)
Banana pseudostems	Santa-Maria et al. (2013), Nzila et al. (2015), Kalia et al. (2000)

(d) Nutrients and Electrical Conductivity

Weiland (2001) reported that the carbon, nitrogen, phosphorus, and potassium are essential for the process of anaerobic digestion as bacterial growth depends on the various nutrients supplied. These nutrients are required at different ratios 500/15/5/3 (C/N/P/S) for hydrolysis and acidogenesis and while 600/15/5/3(C/N/P/S) for methanogenesis. Minimal amounts are required for sulfur and phosphorous compared to other macronutrients. The limiting nutrient was found to be nitrogen, and the carbon/nitrogen (C/N) ratio of 20 to 30 is required (Deublein and Steinhauser 2008; Polprasert 2007). Apart from this, cobalt, nickel, iron, and zinc are required for stimulating methanogenesis. Keratin-rich wastes are produced worldwide by several industries. Angelidaki and Sanders (2004) have observed that if all the insoluble protein (keratin) is converted into soluble protein, the methane potential of keratin wastes is as high as 0.496 Nm3/kgVS. Wu et al. (2020) have investigated the effect of copper salts, cupric sulfate, and cupric glycinate on anaerobic digestion of swine manure. They observed that addition of these salts improved the production of methane by 28.78%. The presence of *Clostridia* and *Methanobacterium* were observed in higher amounts. Lackner et al. (2020) have studied the influence of sulfur addition on microbial community when cellulose was used as substrate in thermophilic digestion. Sulfate addition of 0.5 to 3 g/L caused a decrease in methane generation by 73–92%, while higher sulfate concentrations had no additional inhibitory effect. Upon addition of sulfate, dominance of Firmicutes and decreased concentrations of Bacteroidetes and Euryarchaeota were seen.

The levels of methanogens were reduced, while the levels of sulfate reducing bacteria increased. “Electrical conductivity (EC)” is an estimation of salt content which is measured by an electrical conductivity meter. EC can be used to know if there is an accumulation of any salt taking during anaerobic digestion process. It is important as there are many salts which when accumulated within the process may inhibit the process and thus may decrease the yield of the biogas. It is also used to measure the salts present during the loading of the solid or liquid waste so that its addition does not inhibit the process. To overcome this, generally dilution of the input wastewater is done to keep the value of the electrical conductivity at a minimum.

(e) Toxicity.

Compounds of sulfate and sulfur found in the reactor influence both acetogens and methanogens. This is due to the presence of sulfate-reducing bacteria (SRB) which can use various substrates for survival and are more versatile. Sulfate-reducing bacteria present in the wastewaters convert sulfates, sulfite, and thiosulfate into sulfide. The presence of sulfur compounds reduces the methane yield. At pH 8.0, sulfide remains in the solution, and below pH 8.0, hydrogen sulfide is seen. At pH of 7.0, about 80% of the sulfides is present as hydrogen sulfide. Inhibitory effect of sulfides occurs when the ratio between COD and sulfides is less than 7.7 (Speece 2008). Decreases up to 50% in biogas yield are seen when sulfide concentrations are between 50 and 250 mg/L. This toxicity can be overcome by (Pohland 1992) dilution of the influent, addition of iron salts for precipitating sulfide from solution, or biological sulfide oxidation. Ammonium at 100 mg/L was found to be toxic to the anaerobic digestion process. Salt accumulation can lead to cell death and depends on microbial acclimatization (Ollivier et al. 1994; Appels et al. 2008; Feijoo et al. 1995). Chromium, iron, cobalt, zinc, and nickel have also been reported to be toxic at relevant concentrations (Chen et al. 2008). Phenolic, chlorophenols, halogenated benzenes, and N-substituted aromatic compounds are inhibitory to microorganisms as it interacts with cell membrane (McDonnell 2007). The addition of excess chemical when operating the reactor leads to chemical foaming. The other type of foam is caused due to excess production of biomass in the reactor called biological foam which is usually brown in color. A baffle is used to prevent scum production on the medium where the biomass is generated. Scum is formed due to variation in temperature, mixing, light, and less than four percent of total solids present in the reactor. Both foam and scum formation damage the gas pipes and result in reduction of biogas yield. For regular monitoring of the anaerobic digestion process, fatty acids and total alkalinity are considered. Volatile fatty acids are produced which may cause a change in the pH of the reactor and hence lead to lesser biomass production and biogas. Acetic acid, propionic acid, butyric acid, etc. produced are generally utilized to produce methane. However, at the same time if there levels are high, they tend to cause a change in the pH which needs to be adjusted. This is generally done by means of adding bicarbonate into the digester to keep the pH stable (Boe 2006; Lahav and Morgan 2004). Otherwise there would be a sudden pH drop in the digester. The ratio between fatty acids and total alkalinity is taken into consideration while adjusting the pH of the digester (Deublein and Steinhauser 2011). The ratio should be typically between 0.2 and 0.6, while high pH can also result from the production of ammonia which is mainly seen during the digestion of the protein waste. Methanogenic organisms present in the digester are sensitive to the levels of ammonia. Reducing the input of high protein wastes and addition of iron oxide and clay minerals are reported to reduce the levels of ammonia produced during the process of digestion (Clemens 2013). Sanchez et al. (1996) have reported that iron, nickel, cobalt, copper, and zinc can be responsible for inhibition and cause the failure of the digester. Heavy metals at higher concentration than 10−4 M are inhibitory in nature. This could be due to replacement of metal ions bound with enzymes as prosthetic groups with these ions, causing enzyme inactivation (Chen et al. 2017). The input waste should be properly segregated before the digester is loaded so that any industrial wastes containing metals as such will be separated. The level of EC should be 25–30 dS/m for better operation of the digester. Higher levels of electrical conductivity caused due to the presence of salts can be controlled by dilution with water. The presence of higher amounts of organic matter in the waste material being digested in the reactor can lead to acidification decreasing methane production. When the reactor is in the initial stages, organic loading rate should be increased till a range where efficient production of biogas takes place (Fig. 8.2).

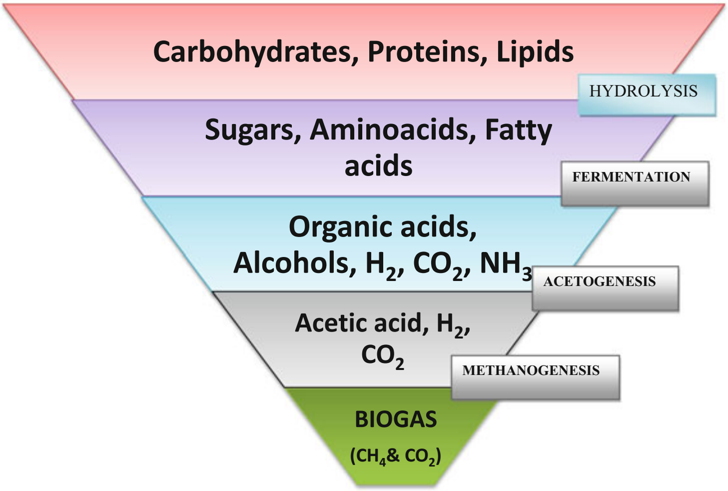

Fig. 8.2 Mechanism of biogas production

8.6 Reactor Design

Bouallagui et al. (2005) have explained different types of bioreactors which are commonly used in the industry: “batch, continuous one-stage system, or continuous two-stage/multi-stage systems.” Some additional modifications are made to the existing models to design “anaerobic sequencing batch reactor (ASBR), upflow anaerobic sludge blanket (UASB) reactor, tubular reactor, plug-flow systems, and anaerobic filters.” Khalid et al. (2011) have opined that among all the reactors. Batch reactors are quick, economical, and simple to operate. The digester tanks used are made of steel and concrete. Among the different types of construction materials being used, concrete constructions are more advantageous compared to others. Generally, the digester tanks are constructed with a lifetime of about 15–20 years. Hydrogen sulfide formation may lead to corrosion of the tank. The mixing system is important as it maintains a homogenous digestate during the process of anaerobic digestion. Longer stirring times are required during the initial phases of operation compared to the later phases of the operation. Ward et al. (2008) have suggested that the design of digester has to address three major issues for competent and economical formation of biogas. Firstly, it should have the capability to handle a high organic loading rate. Secondly, it needs to have a short hydraulic retention time, and lastly it should be able to produce higher volumes of good quality biogas. In this process, the highest methane production is seen in the beginning. Figure 8.3 shows the construction of a thermophilic anaerobic digester used for methane production. In the process of continuous digestion, these are fed continuously; after digestion, the digestate is discharged leading to a steady state for constant gas production rate. These types of systems are dependent on substrates which can be pumped into the system without any mechanical hindrance. If it is not possible, a semi-continuous process is experimented where the feedstock is fed at several times. “Continuous stirred-tank reactors (CSTR) (Fig. 8.4) and plug-flow reactors (PFR)” are the two most commonly used reactors, while others are less used. The plug flow reactors are generally used for dry digestion with the feedstock which contains a lot of solid mass (Patinvoh et al. 2016a). On the other hand, CSTRs are used only in systems where there is continuous supply of feedstock to the reactor such as in wet digestion systems. The decision to use either of the other mentioned systems depends upon the solid contents which are present in the feedstock. Mostly, CSTR design is used in single-stage systems favoring acidogens and methanogens. These are economical and easy to operate (Vandevivere et al. 2003). In the case of two-stage reactors, the process of acetogenesis is separate from that of acidification and takes places in two stages. The first phase favors growth of acidogens, and the pH is generally kept low and acidic. In the case of second phase, the pH is increased favoring the growth of methanogens (Ince 1998). Chaudhary (2008) has observed that the rate-limiting issue in the second stage is the growth rate of microorganisms. Hence, biomass retention times are longer in this phase (Verma 2002). Chaudhary (2008) have noticed that these kinds of systems are more stable compared to single-stage systems. Griffin (2012) has opined that better process control and optimization can

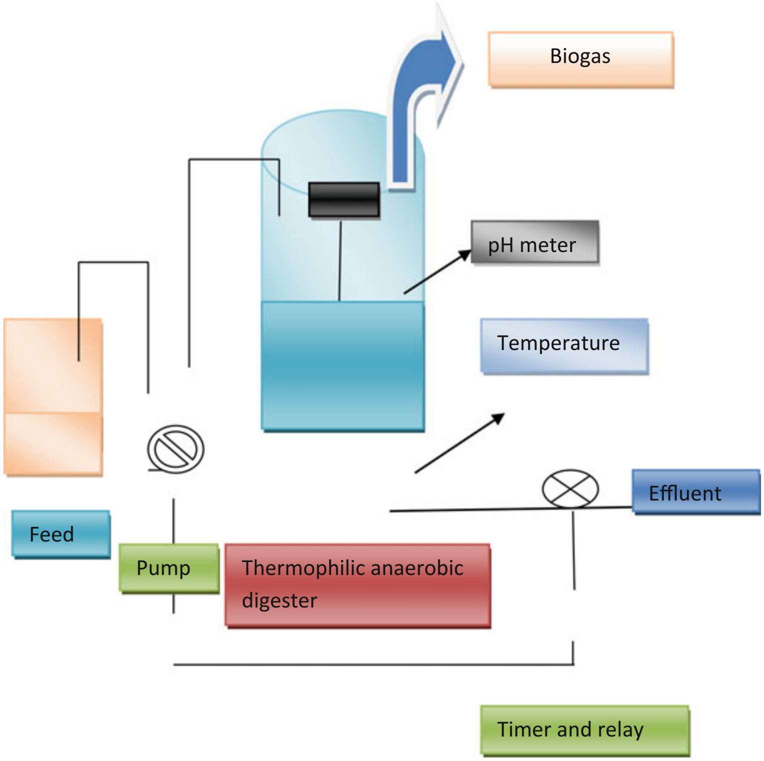

Fig. 8.3 Thermophilic anaerobic digester

take place in multistage reactors. Westerholm et al. (2020) have compared mesophilic and thermophilic industrial-scale plug-flow digesters. The high-solid treatment (HST) demonstrated showed good biogas yields from food waste. In thermophilic HSTs, the abundance of Clostridia group MBA03 while in mesophilic HST abundance of Cloacimonetes was seen. Figure 8.5 shows the construction of a floating drum digester.

8.7 Advantages and Disadvantages of Anaerobic Treatment

The advantages of the process (Gerbens and Zeeman 1999) include provision of energy source through methane recovery, consumption of lower amounts of energy, reduction of solids to be handled, sludge production, raw waste stabilization, less odor, retention of the fertilizer nutrients nitrogen (N), phosphate (P), and potassium (K). The volume of the reactor is generally small and can handle higher loading rates. This process requires less amounts of energy compared to the aerobic process of treatment of waste as biomass generation required is comparatively lower than

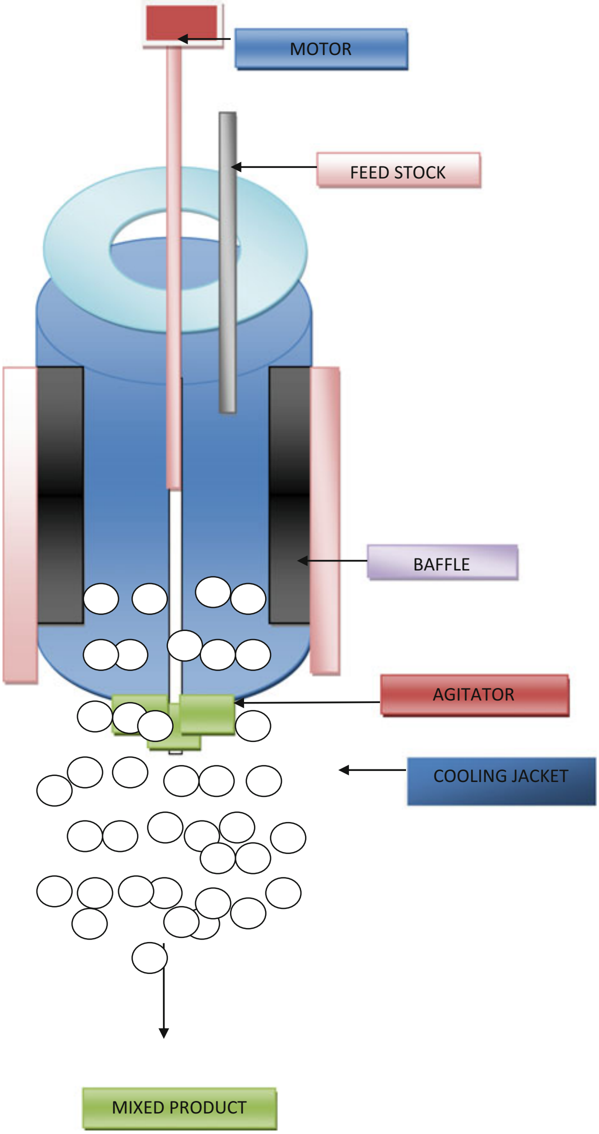

Fig. 8.4 Continuous stirred tank reactor (CSTR)

aerobic process. Since the biomass required is less, the nutrient concentration required is very less. After a shutdown period, when nutrients are added the plant operation starts quickly. The process generates slurry and a fibrous fertilizer. The process is versatile for treating different types of wastes and is eco-friendly. The process generates methane, which can be used as biofuel. Moreover, the process is not energy intensive. The major disadvantage of anaerobic treatment process is that it is not capable of removing inorganic pollutants which are present in the waste and

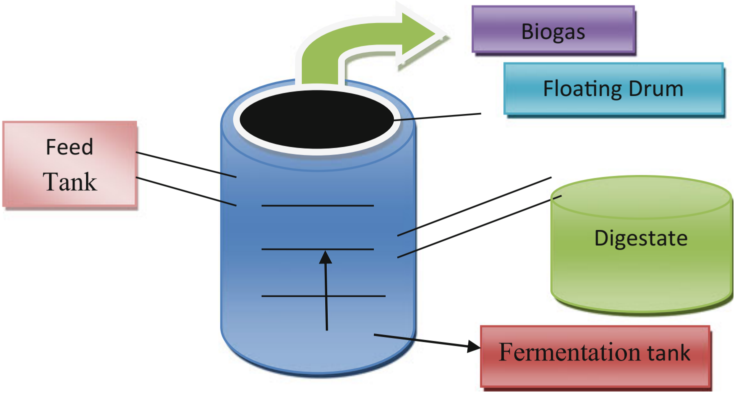

Fig. 8.5 Floating drum digester

any pathogenic organism present in the waste. Only when the reactor is run under thermophilic conditions where high temperatures are used, pathogenic bacteria will not survive; the effluent released may lead to zoonotic diseases if pathogenic organisms survive. Anaerobic processes cannot handle if excess amounts of industrial effluents containing waste are treated as they contain mostly heavy metals which may hinder the process of digestion. It is always better to see that the feedstock is homogenous and steady. The amount of investment for maintaining an anaerobic digestion plant is high. It is not efficient as that of gasification procedure which is used for conversion of carbon to biogas. The anaerobic treatment can be accompanied by odor due to the formation of sulfide. This is one of the most seen disadvantages which are commonly found during the process of anaerobic digestion due to which the area around the biogas plant gets exposed to this foul smell. Moreover, there cannot be any inhabitation because of the smell which emanates from these plants. One of the effective solutions to this problem is to employ a microaerophilic posttreatment step, to convert sulfide to elemental sulfur. This will reduce the odor emanating from the plant.

8.8 Challenges in Biogas Production

The challenges faced are based on the type of waste being treated in the anaerobic digestion. For example, for municipal solid waste, aerobic treatment is preferred compared to anaerobic treatment. This is because it has lower concentrations of biodegradable COD and an effluent which is of better quality as it may be released back into the atmosphere. In the case of industrial effluents which have more concentrations of biodegradable COD, the process will be less expensive. Although the presence of heavy metals should be less in these effluents. Biogas production is challenging considering that there are many factors which need to be optimized and the complex interplay between different microorganisms which are present in different stages of anaerobic digestion. All of these factors affect the production of biogas and lead to its inhibition. The gas produced should be further analyzed and purified. The identification of waste composition, nutrient content of the feedstock, pH, temperature, and reactor design are some of the crucial factors which have to be optimized for enhancing the quality and quantity of biogas being produced (Rasapoor et al. 2020).

A major limitation of current computational enzyme design approaches is the lack of community-wide objective assessment. Recent studies focus on combining processing technologies such as multiple-stage or high-pressure technologies (EBTP-SABS 2016). To improve the AD efficiency, the influence of temperature, pH, C/N ratio, mixing ratios, additives, and other parameters on AD has been studied intensively (Abouelenien et al. 2014; Zhai et al. 2015; Dong et al. 2015). During the AD process, alkalinity is a better indicator of process performance. This can be managed by adjusting pH value; therefore, pH adjustment could provide a way to improve the self-buffering capacity of AD systems to meet the requirements of the microbial populations (Zhang et al. 2016). It affects the activities of the specific acidogenic microbial populations and methanogenic bacteria (Zhang et al. 2012) and consequently influences the process stability (Zhai et al. 2015). They also included different substrates and operational conditions (Jiang et al. 2013; Zhang et al. 2009). Mao et al. (2015) have studied the process performance of anaerobic co-digestion of swine manure and corn straw. Sustainability of the process is the major concern, and many factors have to be taken into consideration when a biogas plant is being established. Apart from those mentioned above, permission from Government agencies for establishing the biogas plant is required. Many factors such as social, environmental, and economic elements have to be considered for sustainability. This process involves a technology which is very simple. One of the major limitations would be to educate the rural population about the benefits of using biogas. Presently, the technology is not very much feasible to be adopted by the rural population as the production depends on number of factors. Many improvements should be made in the production process and the reactor design so that the process becomes feasible and can be adopted by several rural households. Biogas sector requires a long-term vision and good quality control systems, and training mechanisms are essential (Sovacool and Ramana 2015). Public private partnership should be encouraged so that this can facilitate the rural population for start-ups in this area. The development challenge is to seek grants and equity loans from government agencies to support biogas production in rural economy. There are a number of elements such as the migration of the rural population to the urban areas. The limitations of biogas sector include inadequate planning, lack of infrastructure, lack of skilled human resources, and high input costs.

The selection of the feedstock is important as some of the feedstocks will have an inhibitory effect on the process which is called substrate-induced inhibition. This is seen in the processes where the substrate or its byproducts formed after some stages of anaerobic digestion hinder the growth of the microorganism which is helpful for carrying out further stages of the digestion. Hence, the substrate should be properly analyzed, and then optimal conditions for completion of the digestion should be investigated. Many researchers have reported such kinds of inhibitions due to substrate. The substrates which were generally found to hinder the process include pesticides, limonene, furans, metals, and antibiotics (Lallai et al. 2002; Wilkins et al. 2007; Alvarez et al. 2014; Yangin-Gomec and Ozturk 2013). Zabed et al. (2020) have reviewed the production of biogas from microalgae and opined that commercial production of microalgae-based biogas is still in its immature stage and a state-of-the-art technology for producing microalgal biogas is the need of the hour. Excess amounts of proteins and lipids can also cause substrate-induced inhibition. For example, excess amounts of proteins may generate ammonium and hydrogen sulfide which will inhibit microbial growth and change the pH. To overcome these kinds of obstacles, co-digestion is preferred and can lower the toxicity of the substrate or its metabolites. Protein at higher concentrations may result in the formation of ammonia which is toxic for microbial growth (Angelidaki and Ahring 1994). Sousa et al. reported that long chain fatty acids can inhibit the growth of methanogens. Lansing et al. (2008) reported that eutrophication of aquatic ecosystems inhibits the growth of plant and predators which are phototrophic in nature depend on the inorganic carbon levels depleted along with an increase in pH. Certain heavy metals such as nickel, zinc, copper, lead, chromium, cadmium, and mercury also have harmful effect on the environment (Demirel et al. 2013).

Mizuki et al. (1990) reported that limonene (65–88 g/L) can effectively inhibit the anaerobic digestion process. Furans such as hydroxymethylfurfural are produced during the dehydration of carbohydrates present in lignin (Barakat et al. 2012). They are inhibitory to microorganisms present within the digestion process. Monlau et al. (2013) and Barakat et al. (2012) reported that 5-HMF is more inhibitory than other furan compounds and the concentration of the compound should be above 6 g per liter. Pharmaceutical and industrial wastewater consists of antibiotics and pesticides which can be inhibitory to the process (Ji et al. 2013). A raise in the C/N ratio of the feedstock can minimize the production of ammonia by the metabolism of excess protein present in the feedstock (Zeshan et al. 2012). As the ecosystem involved is very complex, anaerobic treatment process needs to be explored further, and the process should be optimized. Only when this is achieved, the process of anaerobic digestion will become sustainable. As long as this is not realized, the process will continue to be a matter of research (Fagbohungbe et al. 2017).

8.9 Conclusions

The use of biogas health and sanitation benefits, ecological and societal benefits. Compressing and bottling biogas would be of really help in commercializing the biogas sector. The use of biogas has been on decline due to urban migration. Many changes are needed such as research and development for optimizing the process parameters and design of bioreactors which are efficient and economical. The present state of giving subsidies to fossil fuels by the Governments should stop so that there is a shift toward investment and research in biogas sector. Biogas as such can have many applications apart from mitigation of greenhouse gas emissions which include different kinds of agricultural operations. If all the above can be done, the process would definitely become economical and create employment for rural population.

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