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Anaerobic digestion fundamentals, challenges, and technological advances

Abstract: Anaerobic digestion (AD) is a natural biochemical process that converts organic materials into combustible biogas. AD has been long practiced for agricultural and urban waste management; however, this process is getting more attention as an alternative energy source nowadays. Additionally, various biogas-derived value-added chemicals and transportation fuels are turning AD into a profitable biorefinery business model. Despite its numerous potentials, AD technologies still face challenges in conversion efficiency, process stability, product quality, and economic feasibility. Researchers have been devising various mechanisms to tackle these challenges. However, a widespread adoption of commercial-scale AD is yet to be visible. The development of AD technology requires a concerted effort of scientists from different backgrounds to ensure rapid expansion.

Keywords: alternative energy; anaerobic digestion; biogas.

1 Introduction

The use of biogas, the product of anaerobic digestion (AD), is known to humankind for hundreds of years. Historical evidence shows that biogas was used for bath water heating in Assyria and Persia during the 10th BC and sixteenth centuries. In the seventeenth century, Jan Baptita Van Helmont first discovered that organic matter decomposition in lakes produces combustible gas or biogas. Sir Humphry Davy first determined the presence of methane in the produced gas in 1808. In the eighteenth century, some anaerobic digestion plants were built in South Asia and slowly transferred to Europe as technology matured. However, the actual mechanism of biogas generation (from organic material decomposition) was unknown till 1930.

Like many other alternative energy technologies, World War II pushed the AD technology forward, and since then, many countries established AD plants, led mainly by European nations. For many years, AD has served as an alternative energy source. Nevertheless, its applications in agricultural and urban waste management often provide more benefits than merely energy production. Municipal wastewater treatment facilities use AD to control odor, reduce waste volume, and increase waste treatment capacity. AD turns the organic fraction of municipal solid waste (OFMSW)

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into biogas resulting in positive impacts on human health, the environment, and the economy. Many industries use AD digesters to manage industrial waste more efficiently with added energy incentives. Although current biogas applications focus on energy production, various biogas-derived value-added chemicals are expanding their economic and environmental potential. This chapter describes the fundamentals of AD and summarizes challenges and recent developments in AD technology and applications.

2 Anaerobic digestion

Anaerobic digestion (AD) consists of a series of biochemical reactions where bacteria break down the organic matters of any substrate into a gaseous mixture (CH_4 , CO_2 , H_2 , H_2S , etc.) in the absence of free oxygen. Some groups of bacteria involved in the digestion process cannot survive in the presence of oxygen. Therefore, an anaerobic (oxygen-free) environment is necessary for the process. The AD process typically occurs in a closed vessel. Produced biogas flows out to temporary storage and later on to the end-use applications. The main commercial applications of biogas are heat and electricity generation. After AD, the vessel will contain residual solids and organic matter known as digestate. Digestate can be separated into liquid and solid streams. Both streams contain valuable plant nutrients and can substitute as fertilizer in agricultural applications.

3 Feedstock

AD can process a broad spectrum of feedstock from various sources. In principle, any biodegradable organic matter can be anaerobically digested to produce biogas. Examples of AD feedstocks from different sources are listed in Table 1. Feedstock for the AD should be readily biodegradable and free of any toxic components that would impact the bacteria. Some feedstock requires a pretreatment to enhance biodegradability. Multiple feedstocks can be mixed and codigested, but some feedstock combinations can degrade performance and even halt the AD process.

Livestock manure is one of the most common feedstocks employed in AD because it is readily available in agricultural farms. Despite containing many characteristics favorable for AD (neutral pH, different microbes, a wide variety of nutrients, etc.), they produce a lower amount of biogas than other feedstocks because they are already predigested by the animal intestine. However, manure is often added as a base substrate and codigested with other feedstock because of its desirable characteristics.

Feedstocks such as sewage sludge, slaughterhouse waste, OFMSW may contain harmful toxic components for the AD bacteria. These should be treated to avoid

Table 1: Common anaerobic digestion (AD) feedstocks grouped by waste category.

Category	Source
Agricultural waste	Livestock manure
	Energy crops
	Harvest remains
	Farm mortality
Industrial waste	Food/beverage processing
	Pharmaceutical industry
	Slaughterhouse waste
	Dairy product waste
Municipal waste	Agro-processing residues
	Organic fraction of MSW (OFMSW)
	Sewage sludge
	Yard trimmings
	Food waste from restaurants/cafeteria
	Supermarket waste

collapsing the AD bacteria. It is also essential to remove or minimize non-biodegradable components from the feed to use the digester volume effectively. Woody biomass or feedstock with higher lignin content are not easily digestible in the AD process and require specific pretreatments to break down the biomass structure. Codigestion of different feedstocks can improve the biogas production in AD, given that the resulting nutrients balance is optimum for the AD process. The biogas potential of various commonly used feedstocks is given in Table 2 [1]. The selection of proper feedstock depends on multiple factors such as availability, desired application of AD products, environmental conditions, digester technology, and economic benefits.

4 Anaerobic digestion chemistry

The AD process occurs through multiple steps with complex interactions between different types of microorganisms. Diverse microbial communities collaborate to break down the complex biomass polymers at different stages and turn them into a gaseous mixture. The biochemical AD reactions can be divided into four distinct stages: i) hydrolysis, ii) acidogenesis, iii) acetogenesis, and iv) methanogenesis, as shown in Figure 1. Specific groups of bacteria are more active than others at different stages. The products of one stage are used as the input for the later stages. Each stage is described in the following section.

Hydrolysis: This is essentially the first stage of the digestion process. Water and extracellular enzymes break down the complex polymeric structure of cellulose,

Table 2: Methane production potential and carbon to nitrogen ratio of different feedstocks [1].

Substrate	Methane potential (mL/g VS)	C/N	Location
Food Waste	435	14.8	United States
Festulolium and Tall Fescue	393	N/A	Denmark
Dairy Manure	177	22.1	China
Chicken Manure	127	8.8	China
Wheat Straw	121	82	China
Winter Harvested Switchgrass	140	491	United States
Summer Harvested Switchgrass	205	92	United States
Chinese Maize Varieties	274	N/A	China
Cow Dung	133	24	Denmark
Sheep Manure	105	19	Denmark
Chicken Litter	105	10	Denmark
Leaves/Straw	45	56	Denmark
Food Wastes	199	14	Denmark
Pine Wood	492	N/A	Finland
Corn Leachate	107	N/A	United States
Dairy Manure	243	N/A	United States
Corn Silage	296	N/A	United States
Used Vegetable Oil	649	N/A	United States
Cheese Whey	424	N/A	United States
Plain Pasta	326	N/A	United States

starch, proteins and convert them into their respective simple units (monomers or oligomers) such as glucose, fatty acids, and amino acids. The generic hydrolysis reaction is shown in Equation (1),

Hydrolytic enzymes generally include amylase, cellulase, lipase, protease, and pectinase. Typically, the growth rate of hydrolytic bacteria is very fast. However, for lignin-rich substrates, the breakdown of polymers turns into the rate-limiting stage. Some compounds in this stage are ready to be converted into biogas, but most compounds need further breakdown through other stages.

Acidogenesis: The products of hydrolysis are further broken down in the acidogenesis stage by acidogenic bacteria. Hydrolytic products are mainly transformed into short-chain volatile fatty acid (VFA) (acetic acid, propionic acid, formic acid, and lactic acid), alcohol (ethanol, methanol), and ketones (glycerol and acetone). CO₂, H₂, NH₃, alcohols, and trace amounts of other products are also generated as byproducts. Some products, such as CO₂, H₂, acetate, and formats, are readily usable by the methanogens at the last stage. Other products need to be further decomposed for the methane production stage. Acidogenesis is generally a very fast process, and there is a

Figure 1: Anaerobic digestion (AD) biomass decomposition stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) and key compounds.

risk of VFA accumulation in the digester, resulting in digester toxicity if not properly controlled. Equations (2)–(4) illustrate the chemical reactions in the acidogenesis stage.

Acetogenesis: Acetogenic bacteria transforms the products of the acidogenesis stage and some of the long-chain fatty acids from the hydrolysis stage into acetate, CO₂, and H₂. Reactions in the acetogenesis stage are not thermodynamically spontaneous if the partial pressure of H₂ is higher than 10^{−4} atm. Nevertheless, methanogenic bacteria lower this partial pressure by consuming the produced H₂. This syntrophic relation, where some bacteria are fed from other bacteria's products, makes the acetogenesis stage thermodynamically feasible.

This interspecies H_2 transfer is synonymous with electron transfer as H_2 is essentially a proton (H^+) with an additional electron. The rate of this electron transfer can significantly influence the overall digestion rate. Equations (5)–(7) illustrate the chemical reactions in the acetogenesis stage.

Methanogenesis: This is the final stage where methane is produced from all intermediate products of the previous stages. This stage is strictly anaerobic as the methanogenic bacteria cannot survive in the presence of oxygen. CH_3COOH (acetate) and H_2 are converted into CO_2 and CH_4 by two different groups of bacteria, such as acetophilic and hydrogenophilic. Acetophilic bacteria convert acetate into CH_4 and CO_2 , while hydrogenophilic bacteria convert H_2 and CO_2 into CH_4 . The reactions in this stage are illustrated in Equations (8)–(10).

5 AD process parameters

AD bacteria are sensitive to several process conditions. Some critical process parameters are temperature, pH, organic loading rate (OLR), hydraulic retention time (HRT), C/N ratio, etc., as shown in Figure 2. Based on the feedstock properties and surrounding environment, optimization of these parameters controls the efficiency, and speed of the digestion process.

5.1 Temperature

Two temperature ranges are widely accepted as the most favorable temperature for the maximum performance of anaerobic bacteria. A digestion temperature ranging from 55–60 °C is defined as *thermophilic digestion*. Thermophilic digestion requires additional energy (heat) input but provides a higher biogas production rate. However, the process is often unstable. A thermophilic temperature increases the feed degradation rate leading to a shorter hydraulic retention time (HRT). It also generates a high-quality digestate with fewer pathogens.

Mesophilic digestion occurs within the 35–40 °C temperature range. Most of the commercial digesters operate at the mesophilic range. Mesophilic digestion produces

Figure 2: Important anaerobic digestion process parameters.

less biogas than thermophilic digestion. However, it provides a more stable operation with lower operating costs.

Organic Loading Rate (OLR): The OLR describes the input rate of organic material per unit volume of the digester. The OLR can be defined as,

$$\text{OLR} = \frac{Q \times \text{COD}}{V} \quad (11)$$

where Q is the feed flow rate in m^3/day , COD is chemical oxygen demand in ($\text{kg COD}/\text{m}^3$) (a measure of organic material content in any substrate), and V is the reactor volume in m^3 . The OLR depends on the substrate organic matter concentration, and the optimal rate is determined experimentally. Higher than optimal OLR can cause toxicity to the digester leading to a decrease in methanogenic activity, as discussed later. On the other hand, a lower than optimal OLR reduces biogas production.

5.2 Hydraulic Retention Time (HRT)

HRT defines the average duration that the substrate resides in the digester. Substrates should be allowed to stay in the digester for a sufficient time to ensure maximum

conversion of organic materials into biogas. However, a longer HRT requires a larger digester size, as shown in Eq. (12), which increases the digester's capital cost.

$$\text{Digester volume (m}^3\text{)} = \text{HRT (day)} \times \text{substrate input flow rate} \left(\frac{\text{m}^3}{\text{day}} \right) \quad (12)$$

5.3 Carbon/nitrogen (C/N) ratio

The substrate C/N ratio is another crucial factor for a balanced AD process. C (carbon) is the energy source for microorganisms, whereas they require a certain amount of N (nitrogen) for their growth or metabolism. The optimal C/N ratio ranges from 20 to 30 for most AD, depending on the substrate characteristics [2]. A low C/N ratio represents a higher N concentration, which will eventually turn into excess ammonia. Excess ammonia produces higher digester alkalinity and inhibits the digestion process resulting in lower biogas yield.

On the other hand, a high C/N ratio means a deficiency of N in the substrate. Microorganisms will readily consume the N, and not enough N will be available for their metabolism. Adding C or N-rich organic material to the substrate to achieve an optimum C/N ratio is common in the AD process.

5.4 pH

The pH defines the concentration of H (Hydrogen) in any solution. Most microorganisms prefer a neutral pH range. Methanogens are very sensitive to pH and prefer around seven for their highest performance. Hydrolytic and acidogenic bacteria perform better between pH values of 5.5 and 6.5. On the other hand, acidogenic bacteria are more tolerant to a larger pH range [3]. Maintaining an optimum pH for all microorganisms in the same digester is challenging, especially for substrates with varying compositions like sewage sludge.

6 Anaerobic digestion technologies

Anaerobic digestion occurs in a closed tank or vessel, often called a digester, to provide an oxygen-free environment. A wide varieties of AD technologies exist based on the feedstock moisture content, feeding frequency, mixing type, temperature, and other considerations. The main design parameters of AD technologies are shown in Figure 3.

Figure 3: Anaerobic digestion (AD) key technology design parameters.

6.1 Wet versus dry

The *wet digester* is the most common type of digester, where the feedstock moisture content is more than 85%. Feeds are mechanically stirred to prevent solid precipitation. Generally, substrates are continuously fed to the digester and removed after a specific HRT. Feedstocks with high moisture content such as sewage sludge and animal manure employ a wet digestion process due to the high energy demand required to reduce their moisture content.

Dry digesters are suitable for feedstock with a higher solid content (>15%). Typically, the feedstocks are stacked in a sealed tank, and hot water or slurry is spread over them to provide a specific digestion temperature. Substrates like solid animal manure, biosolids from municipal solid waste (MSW), food waste, yard trimmings, and energy crops are suitable for the dry digestion process.

6.2 Batch versus continuous

In a *batch digester*, feedstocks are added at the beginning of the process and kept covered for a specific period. The digester is emptied before adding the next batch of feedstocks. Operation and maintenance of a batch digester are simple, but the biogas production is periodic. In a *continuous digester*, feedstocks are continuously added, and biogas and digestates are removed at a similar rate. Continuous digesters constantly produce biogas with minimum digester downtime. In practice, most digesters operate as semibatch, or semicontinuous, in that they allow continuous operation but require periodic maintenance.

6.3 No-mixing versus complete mixing

Mixing of AD feedstock is vital to provide a uniform environment and avoid composition and thermal dead-spots. These are pockets where the substrate is no longer being digested and occupies unnecessary volume or even concentrates toxic compounds. Feedstocks with high moisture contents often do not require mixing. An example of a nonmixing digester is a covered lagoon. Feedstock mixing can be done in different ways, such as mechanical agitation, biogas recirculation, recirculation of digester content using a pump or nozzle. Mixing requires a complex digester design, and operating costs are higher compared to their nonmixing counterpart. However, higher biogas production can offset the increased production costs.

7 Common digester designs

There are several standard digester designs for AD. The optimal choice of digester design depends on multiple considerations, including feedstock composition, environmental temperature, and microbial requirements. Table 3 summarizes the key characteristics of digester designs and their advantages or disadvantages. Following is a detailed discussion of the standard digester designs.

Table 3: Properties (feedstock solid content, hydraulic retention time, and temperature) and comparison of different types of digester design.

Digester type	Total solid (%)	HRT (days)	Temperature range	Advantages	Disadvantages
Covered lagoon	0.5–2	30–40	Psychrophilic	Operating cost is very low	Not suitable for colder region
Complete mix	3–10	10–25	Mesophilic/thermophilic	Suitable for different ambient conditions Can tolerate feedstock variations	Higher energy demand for mixing
Plug flow	10–15	10–25	Mesophilic/thermophilic	Operating cost is low Can digest high solid feedstock	Solids can be settled on the bottom
Fixed film	1–5	>5	Mesophilic/thermophilic	HRT is very low Digester size is smaller	Digester media can be plugged with solid content

7.1 Covered lagoon

Covered lagoons are the most straightforward anaerobic digester technology where feedstocks are stored in an underground lagoon, covered with a gas-tight flexible cover, as shown in Figure 4. Lagoons serve simultaneously as storage and reactor. A covered lagoon sometimes consists of two connected lagoons in series. The first one (cell 1) acts as the digester for biogas production. The second one (cell 2) contains the digester effluent for further processing. These digesters are best suited for warmer regions where the ambient temperature is sufficient to provide the required digestion temperature. Feedstocks with low solid content (0.5–2%) are optimal for this type of digester due to the easy and inexpensive handling of larger volumes. The typical HRT is 30–45 days. Often, screening larger solid particles from the feedstock is necessary to prevent a crust from forming on the lagoon surface to lower the biogas production efficiency.

7.2 Complete mix

A complete mix digester is an above-ground tank made of insulated concrete or steel, as shown in Figure 5. A rigid or flexible cover is used to hold the produced biogas and later collect via gas collecting pipes. Heat exchangers maintain the digestion temperature, and generally, a mechanical mixing system is attached to ensure complete mixing of the feedstock. Complete mix digesters can handle non-homogeneous feedstock with higher solid content (3–10%) feedstock and are suitable for any ambient conditions. The HRT is lower than for a covered lagoon, and it typically ranges from 10 to 25 days.

Figure 4: Schematic diagram of a covered lagoon digester.

Figure 5: Schematic diagram of a completely mixed anaerobic digester.

7.3 Plug flow

Plug flow digesters function similarly to the complete mix digester, except for the feedstock having no mechanical mixing. The plug flow digester is a horizontal, cylindrical shape reactor where feedstock enters from one end and the digestate exits from the other end, as shown in Figure 6. The incoming feedstock pushes out an equal amount of substrate while digestion occurs along the way. Plug flow digesters are typically in-ground and covered with a flexible cover. The feedstock solid content needs to be high (>10–15%) to ensure fluid movement through the reactor.

7.4 Fixed film digesters

This digester design supports microbial growth as a thin film on the surface, often called a biofilm. A column packed with supporting media such as a small plastic ring or wood chips is placed inside the digester, as shown in Figure 7. Not all substrates can be

Figure 6: Schematic diagram of plug flow anaerobic digester.

Figure 7: Schematic diagram of a fixed film anaerobic digester.

used for this type of digester as the packed column has a very narrow space for the substrate flow. The acceptable solid content for this type of digester is 1–2%; higher solids can clog the substrate flow through the digester media. A shorter HRT, typically 2–6 days, is the main characteristic of this digester type, resulting in a smaller digester volume.

8 Challenges with the AD process

Despite being a mature technology, AD still suffers from various challenges limiting its widespread application. Some of the significant challenges include feedstock variability, low process efficiency, and low product quality.

Feedstock variability: Ideally, any biodegradable organic material can be digested for energy production. However, the wide variability in feedstocks' physical and chemical properties is challenging for proper technology selection. Physical characteristics such as feedstock size and moisture content need to be compatible with the digester technology. Too much or too low moisture content creates difficulties in digester feeding and affects bacterial growth in the system. Cellulose, hemicellulose, and lignin-based materials such as animal manure, agricultural residues are the primary candidate feedstock. However, high lignin content reduces the biodegradability of the substrate due to its recalcitrant nature resulting in a slower hydrolysis stage.

Attaining optimal C/N ratio for the anaerobic digestion, as described before, is often challenging with many available feedstock types. Inhomogeneity within the same feedstock, such as wastewater sludge or food waste, is often responsible for

process performance fluctuation. Therefore, maintaining optimum process conditions is a major challenge to process performance.

Low process efficiency: As discussed previously, four different types of bacteria break down the organic materials in four stages. Each type of bacteria requires specific process conditions (such as temperature, pH, and C/N ratio) to function properly. Due to the syntrophic relations among bacteria at different stages, disruption in one stage produces cascading effects on other stages.

Higher accumulation of several intermediate products (NH_3 , VFA, LCFA, etc.) during digestion is detrimental for the microbes, resulting in process inhibition. NH_3 is usually produced during the digestion of nitrogen-rich substrates such as food waste, slaughterhouse waste, etc. Some amount of NH_3 is necessary as nutrients of the microorganisms. However, beyond a threshold level, NH_3 damages VFA consuming methanogens lowering methane production. This further creates VFA accumulation and reduced digester pH. VFA accumulation can also be caused by higher OLR. Accumulation of long-chain fatty acids (LCFA) is also inhibitory for the methanogens. LCFA can accumulate from the lipid-rich substrates during the hydrolysis stage. Higher accumulation of molecular hydrogen in the acetogenesis stage reduces the conversion of LCFA into CH_4 . The combined effect of NH_3 , VFA, LCFA accumulation, and pH fluctuations reduce biogas production and sometimes lead to digester failure.

Lower product quality: Biogas is the main product of the AD process, and it has a lower calorific value than its natural gas counterpart. The presence of more than 40% CO_2 reduces the biogas-specific energy content, flame speed, and increases transportation costs. The electricity production efficiency from biogas combustion ranges from 35 to 42%. The rest is converted into heat and used for the digester heat supply. The combined heat and power (CHP) engine increase the conversion efficiency up to 80%. Nevertheless, most of the time, the produced heat dissipates to the environment without gaining any economic value.

Another AD coproduct is the unconverted substrate as digestate. Digestate is mostly used for soil application as a replacement for chemical fertilizer due to its nutrients value. The high moisture content of digestate often requires solid–liquid separation for easy transportation and storage. Nevertheless, the separation process reduces the digestate nutrient value. Managing a high volume of digestate is also challenging. Energy and cost-intensive posttreatment processes may require producing value-added products from digestate.

9 Conventional processes for overcoming challenges

A broad spectrum of techniques is available for overcoming the challenges mentioned above. Not all types of techniques are applicable for every digestion technology. The

suitable method depends on the feedstock type, digestion technology, and targeted outcomes.

Various thermal, chemical, and mechanical pretreatment methods are available to improve the hydrolysis or solubility of the digester's organic materials. Conventional heating of the substrate increases their solubility in water. It also provides a pathogen-free feed to avoid process inhibition. This is specifically useful for industrial-scale wastewater treatment. Recently, microwave irradiation is being considered as a low-energy alternative. This technique uses focused direct heat to improve the degradability of complex polymers. For lignin-rich substrate, the addition of acids or bases can improve solubility and enhance biogas production. Although energy and cost-intensive, the addition of oxidants is useful when the waste substrate mainly consists of the recalcitrant component such as lignin. Mechanical pretreatment methods such as grinding, shredding, milling, or screening are commonly used for improving digestion efficiency. This method mainly increases the molecule surface area and enhances bacterial activity during the digestion process. High-pressure homogenization (HPH) is another pretreatment technique to homogenize the substrate. Substrate cell membranes are disrupted using high pressure (30–150 MPa) induced shear.

Process inhibitions due to accumulation of harmful intermediate products and nutrients imbalance are minimized via different techniques. Optimizing OLR is a common approach to reduce VFA accumulation. Mono-digestion of any substrate is inefficient because of nutrients imbalance and lack of microorganism diversity [3]. Codigestion or adding other organic materials helps to maintain nutrient balance and avoid process inhibition. Codigestion is also applicable for ensuring optimum C/N ratio. Typically, the carbohydrate-rich substrate is added to the nitrogen-rich substrate, such as animal manure.

Additives are used in the digester for improving material conversion and biogas production. The primary role of additives is to support microbial growth, adsorption of inhibitory products, nutrient supplementation, and enhancing buffering capacity [4]. Various conductive materials such as sand, molecular sieve, zeolite, charcoal, etc., are used to improve syntrophic activity while providing habitat for microbial growth [5]. They can also adsorb inhibitory products like NH_3 , H_2S resulting in more efficient conversion. If any substrate lacks specific nutrients necessary for the digestion process, micro- and macro-nutrient supplements are added to the digester. It stimulates biogas production while maintaining process stability [6].

10 Applications of anaerobic digestion

Anaerobic digestion has attracted attention due to its diverse applications to support environmental protection and potential to create economic benefits. AD has been

considered an effective waste treatment strategy that provides a means of waste volume reduction, odor minimization, and creates multiple revenue streams.

As a waste treatment method, AD has been long used for wastewater treatment. AD helps divert a massive amount of agricultural residues and food waste from landfills or other disposal methods that are environmentally harmful. Many industries are using AD to treat wastewater, minimize the waste treatment costs, and create additional revenue sources when produced biogas is used as an energy source. Confining odor-emitting manure in the digesters is helping livestock farms to solve a critical problem. AD process destroys many environmentally harmful pathogens in the manure.

AD is considered one of the potential renewable energy sources and is in many aspects' superior to others. Turning the waste that would be anyhow generated into energy is environmentally benign and economically profitable with incentives. Biogas produced from AD can be directly used as a replacement for natural gas, although some upgrading may be necessary depending on the end-application. Various tailor-made internal combustion engines are available that are used for electricity production using raw biogas. Combined heat and power (CHP) generators are widely employed technology in many AD plants to produce heat and electricity simultaneously. In many countries, biogas-produced electricity is directly supplied to the main grid. The heat produced by CHP is mainly used within the facility; but in some places, excess heat is provided to the district heating network.

Approximately 80% of the substrate remains in the digester after the digestion process as digestate and retains most of the original nutrient values. This digestate contains nitrogen and phosphorous, which are essential nutrients for plant growth. Therefore, the most beneficial use of digestate is in direct land application as a conventional fertilizer substitute. Digestate nutrients can be separated and applied for a specific purpose. The solid portion of the digestate can be turned into fibers for animal bedding.

Another emerging application of AD is the recovery of intermediate chemicals such as volatile fatty acids (VFA). VFA is a useful substrate for biodegradable plastic production and bio-energy [7]. Upgraded biogas can be turned into many platform chemicals and fuels, valorizing the waste feedstock even more [8].

11 Advanced anaerobic digestion technologies

Most of the advancements in AD technologies are for feedstock pretreatment. Feedstock pretreatment enhances substrate digestion as well as biogas production. It reduces the retention time and allows to build small-scale digesters. Examples of advanced pretreatment methods include ultrasound, use of microbial enzymes, use of pulsating electrical fields, thermal wet oxidation process, use of vacuum, etc. [9]. Although not every method is applicable for all digester applications, combinations of more than one method have already proven effective in enhancing performance.

A critical concern for the AD process is the organic loading rate (OLR). Improper OLR leads to process inhibition and sometimes causes digester failure. Modern reactor designs focus on achieving a high and sustainable loading rate with minimum retention time. The main principle is to trap the methane-forming bacteria in the digester, unlike conventional designs, where bacteria flow with the substrate. Anaerobic sequencing batch reactor (ASBR), anaerobic filter, anaerobic fluidized bed, up-flow anaerobic sludge blanket (UASB) reactor, anaerobic baffled reactor (ABR) are some of the advanced high rate digester design concepts.

Two-staged or two-phased anaerobic digesters are becoming common design practice for better performance. As discussed before, acidogenic bacteria require different process conditions (pH, temperature) than methanogenic bacteria. In a two-staged digester, two digesters are connected in series. The first digester is designed for the acid-producing stages (hydrolysis and acidogenesis). The second digester is for the methane-producing stages (acetogenesis and methanogenesis). Each digester is separately controlled to provide the best process conditions for the respective bacterial group.

Digester disruption can occur due to poor substrate composition, accidental inclusion of toxic substrates, improper loading rate, or various other process parameters. Advanced digester technology uses a complex process monitoring system to give real-time information about the digester conditions [10]. Digester VFA concentration is an important control parameter to signal the process condition and needs to be monitored. The use of multivariate sensors and several analytical methods have made monitoring and controlling more effective.

Process instability leads to reduced biogas production and sometimes total process failure. This is a significant challenge for any commercial-scale AD plant. Lack of balanced nutrients in the substrate is often responsible for this instability due to pH fluctuations, especially in the monodigestion process [6]. Using nutrients supplements helps maintain nutrients balance in the digester. With the expanding knowledge on the biochemical reaction kinetics of AD, the list of new additives is growing.

Biochar (a carbonaceous material produced by thermal decomposition of biomass in the absence of oxygen) is an emerging additive that can increase AD performance by simultaneously counteracting multiple challenges [11]. Biochar adsorbs inhibitory elements (NH_3 , H_2S , etc.) produced during the digestion process and improves the digester buffering capacity by supplying alkaline earth metals. It also accelerates syntrophic metabolism among different groups of bacteria by acting as a Hydrogen transfer medium. Although the exact kinetics of biochar in the AD process are not fully understood, its positive influence on increasing AD performance is well documented in the literature [12]. The use of charcoal and zeolite also have similar effects on the AD system. However, more than optimum dosage is inhibitory for the AD process.

12 Conclusions

AD is an established waste management strategy with a long history. It provides a sustainable solution to conventional waste management problems such as odor minimization and greenhouse gas (GHG) reduction. Recent interest in AD is mainly due to its significant potential to turn waste into various energy products. Biogas and biogas-derived chemical products are becoming more competitive with other renewable energy sources as the technology improves. Moreover, industrial and urban waste are also becoming sources of energy and revenue due to increasing concerns around their environmental and human impacts. Public incentives to reduce waste are helping make biogas an economic natural gas substitute for transportation fuel.

Several challenges remain for the digestion of potential feedstocks. Low biodegradability, process inhibitions, and digester toxicity are still limiting the adaptation of many potential feedstocks. Although various techniques are being investigated to mitigate these challenges, economic viability is a major roadblock for their implementation. The development of AD technology requires a concerted effort of multidisciplinary research communities to continue its business scale adoption and implementation.

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