

Combining Anaerobic Digestion and Waste-To-Energy

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Abstract

A large fraction of the municipal solid wastes (MSW) stream in the U.S. comprises of natural organic compounds (i.e., food and plant wastes) with high moisture content and low heating value. While these properties are undesirable during the combustion of MSW in waste-to-energy (WTE) plants, they are required for anaerobic digestion (AD). During AD, methane gas is produced that can be captured and used for energy generation. The required long residence times limit the throughput of an AD plant but further development may result in increasing the rates of bioreactions. This paper introduces current AD practices and identifies possible synergies between AD and WTE. It is suggested that co-siting of WTE and AD facilities may result in mutual benefits.

Introduction

The process of anaerobic digestion (AD) makes use of anaerobic bacteria to break down organic waste, converting it into a stable solid and biogas, which is a mixture of carbon dioxide and methane. One of the oldest types of processing, AD is used extensively in rural areas to process farm waste and generate biogas. In North America, AD is used on large farms to treat manure and control odor and at wastewater treatment plants, where anaerobic chambers reduce biological and chemical oxygen demand. European nations, on the other hand, employ AD to process various waste streams, including industrial and agricultural organic waste and the organic fraction of municipal solid waste (OFMSW). By doing so, these countries reduce the

volume of waste being sent to landfill, and therefore decrease methane emissions produced from its decay. In addition, the biogas generated at the AD sites is used to produce electricity and heat that is then sold to utilities, making the facilities profitable.

The opportunity to use AD for the OFMSW exists for the United States and Canada, but there are several obstacles that first must be overcome. The first is simply public perceptions. AD treats putrescible waste and this produces highly unpleasant odors. The not-in-my-backyard (NIMBY) principle is strong for AD treatment plants, despite the fact that operating at negative pressures and using biofilters for fugitive gases can control odors. Another obstacle for AD is the lack of knowledge and of information dissemination in North America. There are very few

companies manufacturing AD equipment, little research is being done outside of the farming community, and no professional trade organizations exist to promote the technology. One way to hasten the adoption of AD is to make the process more efficient and thus decrease its capital costs. This requires speeding up the bioreactions in AD reactors. Municipalities are hesitant to invest in AD because it would require breaking new ground. The few facilities that were attempted, such as in Los Angeles, failed because of poor operations and mismanagement. Finally, environmental policy in the U.S. offers no incentive to avoid landfilling, a cheap and simple but unsustainable waste management strategy within the existing infrastructure. This holds true also for waste-to-energy (WTE) facilities that combust MSW to recover energy in the form of electricity and steam.

In 2002, approximately 28.5 million tons or 7.7% of the 370 million tons MSW in the U.S. were combusted in WTE plants [1]. While AD processes require a relatively high water content, the heating value of MSW increases with decreasing moisture content, which also is better for stable combustion. If the wet stream of MSW could be separated and used for AD, the dry stream could be combusted more efficiently. Consequently, it seems that WTE and AD have synergistic potential. Also, WTE plants, that produce high-pressure steam for the generation of electricity or industrial applications, could provide “waste” steam to AD facilities. The heat of this low-temperature steam is otherwise wasted. Combining WTE and AD plants in industrial eco-parks offer a completely new perspective to sustainable waste management.

Anaerobic digestion

Anaerobic digestion (AD) can be defined as the conversion of organic matter into carbon dioxide, methane, and sludge by employing bacteria in an oxygen-depleted environment. The process of AD is one of the oldest forms of digestion and occurs naturally in the absence of oxygen, such as in bogs,

rice fields, improperly aerated compost facilities, wastewater treatment facilities, livestock fields and landfills. The efficiency and stability of anaerobic digestion can vary significantly with the type of digester used and the parameters of its operation. Important factors are waste (feed) type, digester design, digestion temperature, retention time, pH, bacteria, material flow, organic loading rate, and presence of toxicants. Most of the existing digesters are optimized for specific conditions such as geographic location, type of feedstock, and degree of automation. The digesters range in complexity from simple cylindrical cans with no moving parts to fully automated industrial facilities. The simplest, used in rural China and India, are easy to design and maintain, but require consistent monitoring and are less efficient. The most complex, on the other hand, are designed to automatically adjust when environmental conditions change, such as would occur with a change in the feedstock. These are used in developed nations to treat unpredictable waste flows, such as those from the OFMSW.

Digestion is practiced in two broad categories of solid content: high-solids (dry) digestion, with a typical dry solids content of 25-30%, and low-solids (wet) digestion with a dry solids content of less than 15%. A higher solid content leads to smaller and therefore cheaper reactors. However, more costly pumps and higher wear and tear on the machinery to move denser material (increased maintenance costs) may offset this price savings. Systems with lower solids usually have better mixing and higher degree of digestion. On the other hand, wet digestion requires a higher energy input because there is more substrate to be heated in bigger reactors. For many waste streams, large quantities of water must be added to reduce the solids content, thereby adding to operational cost of dewatering the sludge to reuse process water.

Organic fraction of municipal solid waste

Typically, food and yard wastes can be classified as organic or biodegradable wastes that are suitable as feedstock for anaerobic digestion. MSW include wastes from residential sources (such as households), commercial sources (such as markets, restaurants and hotels) and institutional sources (such as schools and hospitals). The food and plant waste fraction in MSW depends on the locality and also the source of the waste. For example, the US Environmental Protection Agency has estimated that food wastes amount for 11.4% of the total MSW and yard wastes for 12.2% [2]. The organic fraction is considerably higher for restaurants and food processing establishments. It has been shown that an approximate molecular formula for organic wastes would be $C_6H_{10}O_4$ [3]. In the absence of oxygen and presence of anaerobic bacteria, these compounds decompose to yield a biogas that comprises of methane (CH_4) and carbon dioxide (CO_2), and a compost product that, after curing, can be used as soil conditioner [4].

Stages of anaerobic digestion

The process of AD occurs in three loosely defined stages: 1) hydrolysis and acidogenesis, 2) acetogenesis and 3) methanogenesis. Each has a physiologically unique bacteria population responsible for the process, requiring disparate environmental conditions. Digestion is not complete until the substrate has undergone all of these three phases.

In the first stage, complex organic materials are broken down in a catalytic reaction controlled by enzymes into their constituent parts (monomers such as sugars, amino or fatty acids) in a process known as hydrolysis. The hydrolytic phase is relatively slow for raw cellulolytic waste, which contains lignin [6]. For this reason, woody waste is generally not processed anaerobically. The monomers are directly available to the next group of acidogenic bacteria. During acidogenesis, bacteria convert the products of

hydrolysis into simple organic compounds through fermentation and other metabolic processes. The new products are mostly short-chain (volatile) acids, alcohols, and ketones.

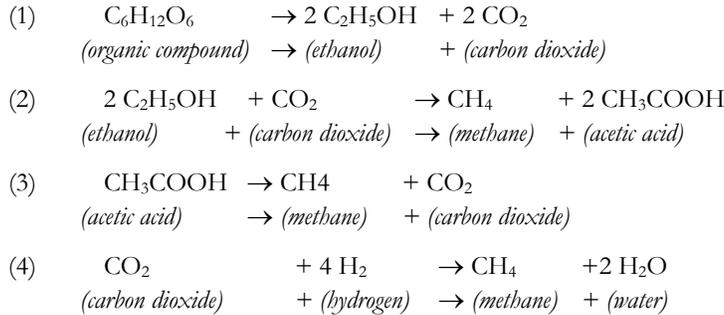
The second stage of AD is acetogenesis, in which acetogenic bacteria convert acids and alcohols into acetate, hydrogen, and carbon dioxide, which are used in the subsequent process. The products formed in this stage vary with the type of bacteria as well as with culture conditions, such as temperature and pH [5]. The transition of the substrate from organic material to organic acids causes the pH of the system to drop. This is beneficial for the acidogenic and acetogenic bacteria that prefer a slightly acidic environment (pH 4.5-5.5) and are less sensitive to changes in the incoming feed stream [6]. Biological oxygen demand (BOD) and chemical oxygen demand (COD) are stabilized in the second stage.

In the third stage, known as methanogenesis or methane fermentation, the same fastidious bacteria that occur naturally in deep sediments or in the rumen of herbivores convert the soluble matter into methane. About two thirds of the methane is derived from acetate conversion and one third is the result of carbon dioxide reduction by hydrogen. [5]. Methanogenic bacteria prefer a neutral to slightly alkaline environment, and are very sensitive to changes [6]. Methanogenesis is the rate-controlling portion of AD because methanogens have a much slower growth rate than acidogens and thereby dominate the kinetics of the entire process [7].

Although AD can be considered to take place in these three stages, all processes occur simultaneously and synergistically (compare Equations 1 to 4). The gas resulting from the sum of these processes is called biogas and is composed of about 45% carbon dioxide and 55% methane [3]. Methane production has been documented under a wide range of temperatures, but bacteria are most productive in either mesophilic conditions, at 25-40°C (77-104°F), or in the thermophilic range, at 50-65°C (122-149°F). A mesophilic digester must be maintained between 30°C and 35°C for optimal functioning [5]. A

thermophilic digester is maintained near 50°C. There are many types and categories for digesters that differ in cost, climate suitability and the concentration of solids they can process.

Typical reactions during anaerobic digestion are [4]:



Types of Digesters and retention time of anaerobic digestion

In AD process technology, two types of reactors are used: the batch process and the continuous process. In the batch process, the substrate is put in the reactor at the beginning of the degradation period and sealed for the duration of digestion. All of the reaction stages occur more or less consecutively and therefore the production of biogas follows a bell curve. Retention time ranges from 30-60 days and only about 1/3 of the tank volume is used for active digestion [7]. The disadvantage of this type of system is the large tank volume required due to the long retention time, the low organic loading rate and the formation of a scum layer.

In the continuous process, fresh substrate is added and an equal amount of effluent is removed continuously, maintaining equilibrium. Reactions occur at a fairly consistent rate resulting in nearly constant biogas production. The reactor used in a continuous process can be similar to a batch process, e.g., a cylindrical tank with influent and effluent valves. Because there is constant movement of material inside the volume, however, the tank does not become stratified. As a result, the effluent is a combination of completely digested and partially digested material and the reported residence time is

the average across the substrate. Several mixed forms of these two models have been developed, including the plug-flow reactor and the sequencing batch-reactor that are designed to combine the advantages of the two extremes types [5]. In a multiple stage system, designers take advantage of the fact that there are distinct stages of digestion, performed by unique species of bacteria that require specific environmental conditions. Multiple tanks are used to allow each tank to be optimized for a particular process.

If AD is to compete with other MSW disposal options, the retention time must be lower than the current standard of 20 days. The retention time is determined by the average time it takes for organic material to digest completely, as measured by the chemical and biological oxygen demand (COD and BOD) of exiting effluent. Speeding up the process, will make the process more efficient. Microorganisms that consume organic material control the rate of digestion that determines the time for which the substrate must remain in the digestion chamber, and therefore the size and cost of the digester.

Though individual bacteria probably cannot be made to digest material quicker, there are several ways to achieve a shorter retention time. Providing a hospitable environment for the population will allow the bacteria to reproduce easier, giving them a greater

working population. Pre-processing the waste so that it is more easily degradable will require fewer bacteria, allowing them to proceed to the final stages of digestion in less time [8]. Mixing the sludge and providing a higher water content will give bacteria greater access to substrate. Finally, providing a substance on which the bacteria can live inside the chamber will prevent a greater number from being washed out, thereby establishing a more stable working population [9, 10]. Some of the most promising research has shown retention times in the 2-5 day range, but this is for very dilute, low solids waste [11, 12].

Combining WTE and AD processes

As noted above, AD processes require a relatively high water content (over 70% for the case of high-solid systems). The more moisture in the original feed, the less water has to be added. On the other hand, the heating value of MSW increases with decreasing moisture content (Figure 1, [13]). If the wet stream of MSW could be separated and used in AD facilities, the dry stream would be more homogeneous and provide a better fuel for WTE processes. WTE plants could provide the necessary heat to ensure stable elevated temperature conditions in digesters by providing the “waste” steam exiting the turbine generator of electricity. In return, AD could provide gas to neighboring WTE facilities during operational start-up and shutdown phases.

Ideally, power-generating facilities can be sited in eco-industrial parks, where heat recovery occurs in three phases: 1) steam for generating electricity, 2) industrial steam, and 3) district heat or heat for AD processes. In this scheme of co-generation, WTE plants could more than double their efficiency [14]. Finally, existing infrastructures of a combined AD/WTE site can also be facilitated for the distribution of compost products after the conversion of AD sludge.

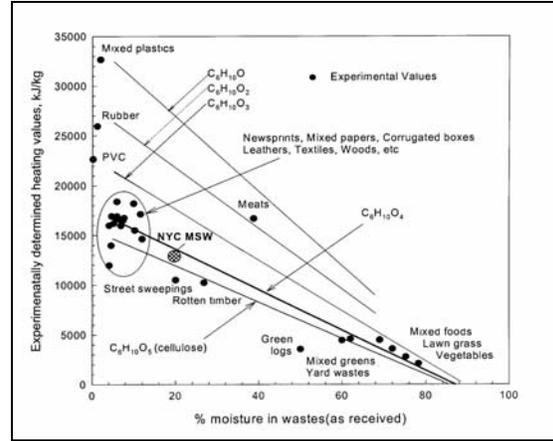


Figure 1: Effect of composition and moisture on heating values of different MSW materials [13]

Although the mutual benefits of combining AD and WTE processes to a sustainable waste management option seem obvious, in case of MSW, the separation of dry and wet streams (or essentially diversion of the OFMSW) will require additional costs during the implementation of an appropriate collection and handling system. It will also be important that the organic fraction remains fairly “uncontaminated” by other MSW compounds to ensure proper digestion. This could be achieved by adding a materials recovery facility to the eco-park that extracts recyclable material from the waste stream and then delivers the wet stream to an adjacent AD facility and the dry stream to a WTE plant (Figure 2). Another related concern is the marketability of the composted residue of AD processes. There has to be a relatively large demand in these products within reasonable distance to make the process economically viable; most likely it will require the use of compost product by local government for public works. Similarly, the beneficial use of combustion residues would promote the acceptability of WTE facilities.

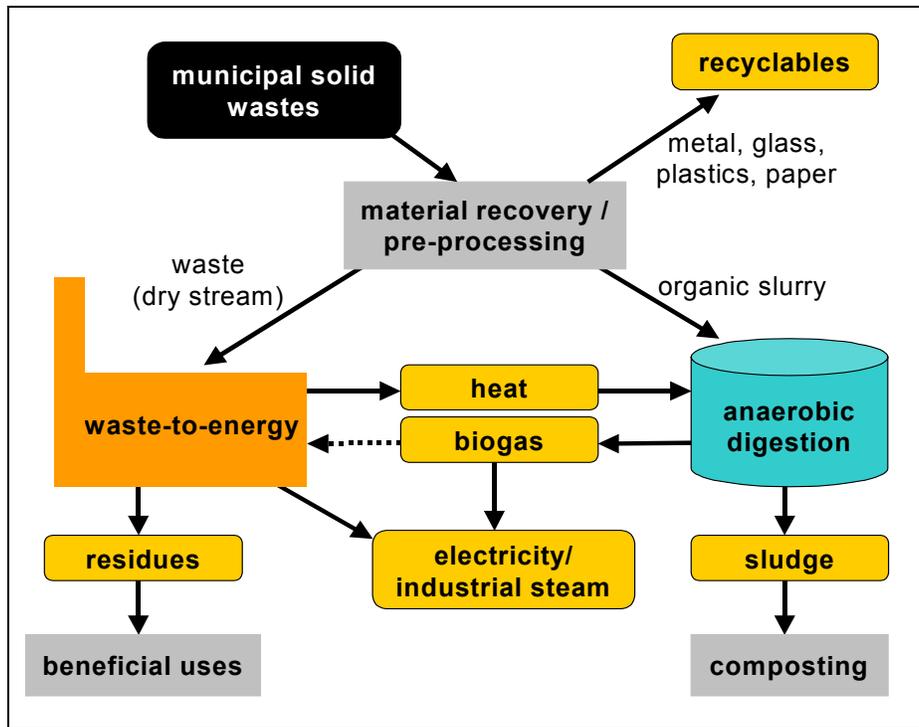


Figure 2: Scheme of eco-industrial park for treating MSW by co-siting MRF, WTE and AD facilities

Conclusions

The European Union has issued a landfill directive that requires the minimization of landfilling within their member communities. Thereby, it has forced the employment of alternative waste management options such as recycling, composting and AD, and combustion for energy recovery (WTE). In contrast, the low prices for landfilling in the U.S. result in comparably low diversion rates of MSW in the U.S. (for 2002: 26.7% recycling and 7.7% WTE [1]). Aside from political/regulatory incentives, the feasibility of AD projects to partially manage MSW and the chances of implementing new AD facilities will increase with reduced retention times of advanced processes and provision of a suitable feedstock. The separation of the organic fraction could benefit WTE processes because the remaining dry waste stream offers a higher heating value. Co-siting AD and WTE facilities might create mutual synergistic effects because “waste” heat from WTE

plants after electricity generation could be used in AD facilities that, in return, could provide biogas. The success of such eco-industrial parks will strongly depend on finding markets for the end products of the involved processes.

In sustainable waste management, AD and WTE processes offer environmental benefits in comparison with landfilling. The use of AD in a controlled environment allows methane to be captured and combusted to produce heat or electricity. Also in WTE plants, the uncontrolled formation and flaring of methane such as practiced in landfills will cause a reduction in released greenhouse gases. However, it will be an enormous challenge to gain the necessary public acceptance for AD and WTE facilities. Other than farm applications, restaurant and institutional wastes hold the most promising prospect to function as feedstock in AD processes for pilot projects in the U.S. because they produce large quantities of “clean” organic waste.

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