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Anaerobic Digestion: Biology and Benefits

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INTRODUCTION

Anaerobic digestion is an engineered methanogenic decomposition of organic matter under oxygen-free conditions and involves a mixed consortium of different species of anaerobic microoganisms that transform organic matter into biogas. The process is successfully used for the treatment of municipal sludge, animal manure, industrial sludge, and industrial and municipal wastewaters. Applications of anaerobic digestion for waste treatment produce significant benefits beyond simple waste removal. These benefits include both energy production and energy conservation. In addition to waste removal, other environmental benefits result from anaerobic digestion including odor reduction, pathogen control, minimizing sludge production, conservation of nutrients, and reduction in greenhouse gas emissions. Unlike fossil fuels, use of renewable resources represents a closed carbon cycle and therefore does not contribute to increases in atmospheric concentrations of carbon dioxide. Replacement of fossil fuels also reduces atmospheric pollutants responsible for acid rain. Thus, anaerobic digestion is both a waste treatment technology, which enhances environmental quality, and a sustainable energy-producing technology.

MICROBIOLOGY

Anaerobic digestion is a process by which a complex mixture of symbiotic microorganisms transforms organic materials under oxygen-free conditions into biogas, nutrients, and additional cell matter, leaving salts and refractory organic matter. Raw biogas typically consists of methane (60%) and carbon dioxide (40%), water vapor and trace amounts of hydrogen sulfide. As much as 90% of the biodegradable organic fraction of a waste can be stabilized in anaerobic treatment by conversion to methane gas.

From the process engineering point of view, anaerobic digestion is relatively simple. Since the process uses a "mixed culture" of ubiquitous organisms, no sterilization steps are required and product separation is unnecessary as the biogas separates itself from the aqueous phase. Indeed, since the methane produced is relatively insoluble, it does not accumulate to inhibitory concentrations in the fermentation mixture. However, the biochemical processes involved in anaerobic digestion are very complex.

An early scheme for the anaerobic digestion process divides the process into two phases, an *acidification* or "acid" phase and a *methanogenic* or "methane" phase, as depicted in Figure 1. This simple scheme shows the principal components of complex organic matter, which are amenable to conversion, as carbohydrates, proteins and lipids.

Complex Organic Matter carbohydrates proteins lipids	⇒ *Acidification*	**Intermediate Volatile Acids** acetate propionate higher acids	⇒ *Methanogenesis*	**Methane** + $\mathbf{CO_2}$

Figure 1. *Simplified scheme for anaerobic digestion of organic matter*

The multiphase nature of the process was subsequently revealed by the discovery of hydrogen-producing acetogenic bacteria and by a better appreciation of the limited substrate capabilities of methanogens (Fig. 2). Thus, anaerobic digestion consists of a series of reactions which are catalyzed by a mixed group of bacteria and through which organic matter is converted in a stepwise fashion to methane and carbon dioxide. Polymers are hydrolyzed to oligomers or monomers, which are then metabolized by fermentative bacteria with the production of hydrogen (H_2), carbon dioxide (CO_2), and volatile organic acids such as acetate, propionate, and butyrate. The volatile organic acids other than acetate are converted to methanogenic precursors (H_2, CO_2, and acetate) by the syntrophic acetogens. Finally, the methanogenic bacteria produce methane (CH_4) from acetate or from H_2 and CO_2. Stable digester operation requires that these bacterial groups be in dynamic equilibrium, as some of the intermediate metabolites (hydrogen, propionate, ammonia, sulfide) can be inhibitory and the pH of the system must remain near neutral. Maintenance of low hydrogen partial pressure, which is primarily dependent upon the activity of the hydrogen-utilizing methanogens, regulates the degradation of propionate and butyrate. The acetate-utilizing methanogens regulate the pH by conversion of acetic acid to methane and CO_2.

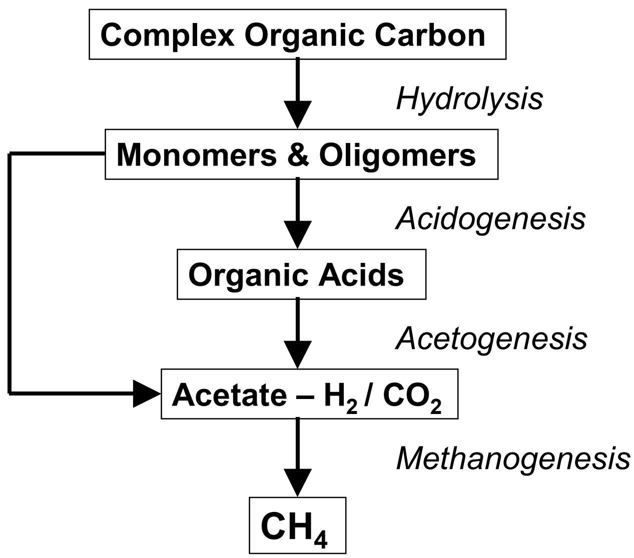

Figure 2. *Multiphase nature of anaerobic digestion*

Almost all known methanogens convert H_2/CO_2 to methane, whilst aceticlastic methanogenesis has been documented for only two methanogenic genera – *Methanosarcina* and *Methanosaeta*. For aceticlastic methanogens, low levels of acetate (< 50 mg/*l*) favor the growth of more filamentous organisms (e.g. *Methanosaeta*) that must rely on a larger surface-to-volume ratio in order to improve substrate diffusion rates. High levels of acetate favor the predominance of clusters of aceticlastic methanogens (e.g. *Methanosarcina*) with lower surface-to-volume ratios that serve to protect them from the inhibitory nature of high organic acid concentrations. Differences in maximum growth rate and substrate utilization affinities can be exploited to select for predominant methanogens. Organisms such as *Methanosarcina* should be favored for selection if high conversion rates of high-strength wastes are the primary goal, while *Methanosaeta* should be favored if low effluent BOD is more important. In addition, these attributes can be exploited together by staging an anaerobic process with the first stage favoring high conversion rates and the next stage favoring effluent quality.

Anaerobic digestion occurs naturally in anaerobic environments such as sediments, soils, and animal intestinal tracts. Biological methanogenesis has been reported at temperatures ranging from 2 ^{o}C (in marine sediments) to over 100 ^{o}C (in geothermal areas). Most anaerobic digestion applications have been performed under either ambient (15-25 ^{o}C), mesophilic (30-40 ^{o}C), or thermophilic (50-60 ^{o}C) temperatures. Digesters with lower temperatures are more stable and require less process energy, but require larger volumes. Typically, most digesters are operated at mesophilic temperatures.

BENEFITS

Energy

The production of biogas from waste materials for use as a fuel energy source qualifies anaerobic digestion as a sustainable technology for renewable energy generation. However, energy production through anaerobic digestion alone may not always prove economically viable in a climate of low energy costs. Yet, applications of anaerobic digestion may produce significant energy savings and the benefits of energy conservation may also have significant economic value. The overall economic balance should include cost comparisons with alternative aerobic treatment systems.

Energy Production

The application of anaerobic digestion to the recovery of energy from wastes may produce significant amounts of renewable biogas fuel. In practice, depending on the proposed use, the biogas may be scrubbed to remove water vapor and hydrogen sulfide. For every 1 kg of COD of a waste that is converted by anaerobic digestion, 0.35 m^3 of CH_4 (dry gas at 0 ^{o}C and 1 atm) is produced. This means that around 12 x 10^6 BTU can result from conversion of every 1000 kg of COD contained in waste materials that is biodegradable. For solid wastes, concentrated manures, and high-strength wastewaters, this level of biogas production is significantly more than the energy requirements of the process.

Energy Conservation

Energy conservation can be achieved by the application of anaerobic digestion instead of conventional aerobic processes. In order to supply oxygen for aerobic treatment, energy is consumed to compress air for aeration of wastewater or to turn and mix solid waste for aerobic composting. In aerobic wastewater treatment, 500-2000 kW-hr of electricity is consumed in order to supply oxygen demand for every 1000 kg COD. The application of anaerobic digestion for wastewater treatment can conserve this same amount of energy for every 1000 kg of COD in the wastewater that the process reduces. The energy savings from avoiding aeration for COD reduction can exceed the energy contained in the biogas produced. These energy savings can reduce electric utility demand and allow this power to be applied elsewhere in productive industrial or residential sectors.

It is possible for the application of anaerobic digestion to effect additional energy conservation as a consequence of the inherent nutrient conservation aspect of the process. Where treated effluents from anaerobic digestion can be applied to productive agricultural lands, the plants benefit from the presence of important plant nutrients including nitrogen and phosphorous, which are retained in the treated effluent. Since sludge production in anaerobic digestion is minimal, virtually all of the nitrogen and phosphorous contained in the original waste is present in the treated effluent. The production of nitrogen fertilizer from atmospheric N_2 requires energy input to "fix" this nitrogen into ammonia and nitrate. Up to 100 ft^3 of CH_4 can be consumed for every lb of N in the fertilizer produced. Likewise, the mining and processing of phosphate minerals into phosphate fertilizers consumes energy. The use of anaerobic digestion for waste treatment along with the application of treated wastes to agricultural lands at appropriate rates for nutrient uptake, therefore, conserves energy through displacing energy-consuming synthetic fertilizer production.

Environmental Quality

The application of anaerobic digestion should be considered for the environmental benefits of the process, in addition to its potential for energy production from waste. There are many potential environmental benefits that can be realized from the application of anaerobic digestion. First, anaerobic digestion reduces the organic content of the waste, which results in a decrease in the COD strength of the wastewater as well as a volume reduction for solid waste materials. This reduction of waste organic content occurs without producing large quantities of by-product sludge requiring further treatment, while preserving the fertilizer value of the wastewater. Organic waste of all sorts can become a nuisance when it becomes a source for odor. Anaerobic digestion removes and contains the biodegradable components of waste, which produce odorous compounds. The application of anaerobic digestion can also reduce the pathogen populations in the waste, which can enhance public health in the location of final waste disposition. Finally, the application of anaerobic digestion can reduce greenhouse gas emissions, which are a cause for potential global warming.

Waste Treatment

As a consequence of the production of methane in biogas, organic matter in waste is reduced and waste is stabilized. While aerobic waste treatment also reduces the organic content of waste, the aerobic process is limited by the supply, the solubility, and the utilization rate of oxygen, which is required for aerobic organic matter reduction. This oxygen limitation also limits the microbial density that can be applied in aerobic treatment. Anaerobic digestion does not require oxygen and is not limited by these factors. This means that, on a treatment volume basis, the organic loading rate which can be applied to anaerobic treatment systems can be 5 to 10 times higher than for aerobic processes treating the same waste. Higher process loading rates translate into lower physical space requirements for the treatment facility. The application of anaerobic digestion, therefore, can result in less land area required for treatment, which in turn increases the land available for other uses.

The application of anaerobic digestion also has the environmental benefit of very low excess sludge production. Sludge produced from waste treatment requires further processing and disposal. In aerobic treatment, up to 50% of the organic matter removed from the waste may be converted to microbial sludge which results in a process that effectively only transforms waste from one form (soluble matter) into another (sludge). In contrast, less than 10% of the organic matter removed from an organic waste is transformed into microbial cells using anaerobic digestion. This low sludge yield also reduces the nutrient requirements for biological treatment. In addition, while the slow growth rates of anaerobic organisms limit sludge production, the sludge can remain stable and biologically active for long periods. Periodic operation of anaerobic digestion processes for wastes that are produced on a seasonal basis (e.g. canning and food processing) benefits from the stability of anaerobic microbial sludge.

Odor Reduction

Anaerobic digestion treatment was developed originally because of its ability to control and eliminate the malodors associated with domestic sludges. Generally, the final products of microbial degradation of carbonaceous material in an anaerobic ecosystem are methane and carbon dioxide, which are both odorless. However, when wastes are stored, the rate of methane production is not fast enough to prevent the accumulation of volatile organic compounds (phenols, indoles and volatile fatty acids). In other words, the acid-forming and methanogenic steps in the microbial degradation of stored organic matter are unbalanced. This imbalance between the processes of acid fermentation and methane production is the key to understanding the accumulation of volatile malodorous products. Under balanced conditions, the VOCs are converted to methane and carbon dioxide.

In many storage systems for organic wastes, therefore, an unbalanced fermentation is created and objectionable odors result from the accumulation of volatile malodorous intermediates. However, in an anaerobic digestion system designed and operated for methane production, the two phases of acid fermentation and methane production are kept in balance and odorants are degraded.

While the intermediate compounds of anaerobic metabolism are a potential source for odor, proper operation of an anaerobic treatment facility reduces these compounds and contains all the gases emitted from the process. The final waste has a lower odor threshold and, on proper combustion, the biogas emissions produce no odor. Although the biogas may be odorous due to traces of hydrogen sulfide, the gas is usually enclosed until it is burned or treated for hydrogen sulfide removal prior to use. High treatment efficiency has been shown to correlate with biological stabilization and permanent odor reduction, whereas failure to remove all fermentable substrates may lead to odor regeneration upon storage of treated waste.

Table 1 compares the impacts of storage and treatment by anaerobic digestion on the threshold odor number (TON) of flushed dairy manure. After 3 days of storage, the odor level of this waste increases by 77% while, after anaerobic treatment, the odor level decreases by 97%.

Table 1. *Change in threshold odor number (TON) for flushed dairy manure after 3-day storage and after anaerobic treatment*

Sample	Threshold Odor Number (TON)*	% Change in TON
Flushed dairy manure	247	0
Flushed dairy manure after 3-day storage	437	+77%
Flushed dairy manure after anaerobic digestion	7	-97%

*TON represents the number of dilutions required for a human odor panel to no longer detect odor.

Pathogen Reduction

In addition to the potential of organic wastes to pollute drinking water supplies and surface water resources, both nuisance odors and pathogens can result from organic wastes, especially municipal sludge and animal waste. The ecological conditions within an anaerobic digester effectively lower levels of pathogens. Starvation and competition with other microorganisms lead to pathogen decimation. Also, the presence of organic acids in anaerobic treatment can serve to inhibit the growth of pathogens and, when thermophilic anaerobic digestion is employed, the high temperatures contribute to greatly reduce pathogen levels. In practice, the level of reduction of pathogens is dependent on both the exposure time and the temperature of the digester. As with odor reduction, high treatment efficiency has been shown to correlate with significant pathogen reduction. Where recycling of wastewater is employed in intensive animal production facilities, the impact of anaerobic digestion-associated pathogen reduction on animal health is positive. Also, by its very nature, the process is totally enclosed and does not produce bacterial aerosols.

Nutrient Recovery

Since anaerobic digestion removes mainly carbon, nutrients contained in the organic matter are conserved and mineralized to more soluble and biologically available forms. This provides a more predictable, quick-release organic fertilizer that can be applied to cropland at appropriate rates for maximum plant nutrient uptake with minimal loss to the environment. However, with a higher percentage of the nitrogen content now in the form of soluble ammonium salts, the rate of ammonia emissions during subsequent storage may be higher. This can be overcome by application of an impermeable cover to the storage facility. Where insufficient cropland is available, other nutrient recovery technologies can be employed to reduce the nutrient content of the digested wastewater.

Greenhouse Gas Reduction

The application of anaerobic digestion has the environmental benefit of reducing the potential for global warming. Both CH_4 and CO_2 are significant greenhouse gases and their presence in the upper atmosphere decreases irradiative heat losses from the earth's surface, effectively trapping heat, which may result in a warming of the planet and cause severe climatic changes. Anaerobic digestion can reduce the potential for global warming in two ways.

First, if anaerobic digestion is employed to produce a renewable fuel which is then used to replace the consumption of fossil fuels such as coal, oil, and natural gas, production of the CO_2 emitted from burning the fossil fuels is avoided. The CO_2 emitted from burning the biogas comes from the carbon in the organic waste, which ultimately came from the atmosphere, and is part of a closed carbon cycle and, therefore, does not contribute to increasing atmospheric CO_2 levels.

The second way in which anaerobic digestion can reduce potential global warming is by reducing CH_4 emissions. Untreated organic waste will undergo uncontrolled anaerobic digestion and methane from these wastes can increase atmospheric methane concentrations. By applying anaerobic digestion to these wastes and capturing and utilizing the biogas, emission of methane to the atmosphere and the greenhouse effects of this methane are avoided.

CONCLUSION

Anaerobic digestion under controlled conditions offers a holistic waste treatment solution that not only stabilizes the wastewater, but also is a net energy producer, controls odors, reduces pathogens, minimizes environmental impact from waste emissions, and maximizes resource recovery. The technology is tolerant to a variety of feedstocks and co-digestion of different organic wastes is also possible. The size of anaerobic digesters can be scaled to match the application and centralized anaerobic digestion plants, treating a combination of organic wastes, can be utilized to achieve economies of scale.

Many of the benefits of anaerobic digestion translate directly to practical and economic benefits that contribute to long-term sustainability. In addition to potential energy cost savings from biogas utilization, anaerobic digestion contributes generally to improved waste management. Anaerobic digestion not only removes malodors but also stabilizes the waste, allowing indefinite storage without putrefaction. Anaerobic digestion of organic municipal waste lowers the requirements for landfill capacity and reduces associated emissions. At the farm level, anaerobic digestion stabilizes manures (permanent odor reduction), allowing them to be stored more easily and for longer periods. Handling costs are also reduced because the digested effluent is easier to pump than raw animal manures. When correctly applied, the by-products of anaerobic digestion (liquid fertilizer and compost) reduce the need for synthetic fertilizers and soil conditioners that are produced using less sustainable methods, providing cost savings as well as environmental benefits. After anaerobic digestion, the nutrient content of the wastewater is more predictable, allowing it to be more precisely applied within a fertilizer management program and reducing wastage. Anaerobic digestion systems, therefore, provide significant benefits to aid in meeting the increasing environmental regulations and public pressures on farmers and others regarding organic waste handling and disposal.

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