Enhanced Anaerobic Digestion of Biomass Waste for Optimized Production of Renewable Energy and Solids for Compost

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Summary

There are millions of tons of biomass waste being produced every year for which disposal is a problem. At the same time the world is rapidly depleting its supply of natural gas, which is known to be the cleanest of the fossil fuels. Anaerobic digestion (AD) is a highly promising technology for converting biomass waste into vast quantities of methane, which may directly be used as an energy source, or converted to hydrogen. However, the full benefits of AD have not been realized because of the perceived costs involved. This paper describes: An alternative low cost approach to anaerobic digestion and energy production. This approach has been developed recently by Oswald (1996 and 1994) and others and initial work has indicated that high concentrations of methane may be produced without the presence of other polluting gases, such as CO2, H_2S and PH_3. At the same time Owens and Chynoweth (1993) and others have shown that nearly all biomass materials can be digested to produce methane, and that the residual solids are odor free and serve as an excellent soil amendment/compost. This process is still underutilized, however, because the system is not well known to the agricultural, industrial and engineering communities.

The objectives of this paper are to:

1.Demonstrate the effectiveness of the deep digester as a cost-effective means of waste-minimization and energy production
2. Describe and explain design criteria for optimal performance
3. Explain the benefits of anaerobic digestion of biomass for farmers, industry, and the general public.

In order to achieve these objectives, a demonstration digester, for the Morwai Dairy near Greeley, Colorado, USA, is described and explained. Various performance indicators are also described and explained using data from in-situ probes in addition to standard laboratory measurements. Additionally, molecular techniques are described which are used to discern the composition and activities of microbial communities. The data collected are utilized to develop models of system function and to optimize the performance of the system with respect to desired microbial populations (lignin and cellulose degraders and methonogens) and ultimately to digester performance (enhanced solids destruction/methane production). The methane collected is to be used for operating dairy farm equipment or sold to a nearby natural gas pipeline. Activist groups are used to prepare and disseminate information for farmers and the general public. Additionally, this project is used to educate students both in the field and in the classroom. In this manner future engineering professionals as well as society at-large is being educated about the benefits of anaerobic digestion. This project, therefore is addressing multiple goals,

including: improved rural-based biomass processing techniques, development of abundant, commercially relevant, and sustainable energy sources as well as a sound strategy for enhancing economic viability and public awareness.

Key words: anaerobic digestion; methane production, cleaning, and use; use of digested solids.

Introduction

It is estimated that 200 million tons of municipal solid waste is generated in the U.S.A. each year (US EPA, 1999), and that 80% of it is biomass that is biodegradable by at least 50%, and much of it is essentially 100% biodegradable (Owens and Chynoweth, 1993). In addition, total manure produced in US from all livestock and poultry is estimated to be 335 million tons dry matter/year (with a moisture content of about 90-95%) (ARS Report, 2001). At the same time that these massive quantities of "waste" are being produced, the world is rapidly depleting its supply of natural gas, which is known as the cleanest of the fossil fuels. Anaerobic digestion of biomass waste is a highly promising approach to producing vast quantities of methane, which typically comprises ca. 93% of natural gas. Methane may also serve as the raw material for hydrogen production. Methane thus has great potential as an abundant and <u>renewable energy resource</u>. Table 1 (animal waste) and Table 2 (municipal solid waste) provide an indication of the tremendous quantities of methane that may be produced from waste biomass while at the same time alleviating the problem of waste management through the beneficial use of stabilized

Table 1: Production of Waste Biomass by Animal Type and Potential Methane Production in the USA

Animal Type	**Number in U.S. in FY2001 (ref 1)**	**Typical Animal Mass, kg**	**VS/day/1000 Kg Animal Mass**	**Maximum Methane Production Capacity, B_o m^3 CH_4/kg-VS**	**Methane Produced per Day, m^3 CH_4/day**
Beef & Dairy Cattle	99,324,500	500.5	7.2 kg VS	0.17 – 0.33 m^3 CH_4	60.8 - 118·10^6 m^3 CH_4/day
			Day · 1000 kg animal mass	kg-VS	
Sheep & goats	7,615,600	65.5	9.3 kg VS	0.19 – 0.36 m^3 CH_4	8.81 - 16.7·10^5 m^3 CH_4/day
			Day · 1000 kg animal mass	kg-VS	
Poultry	8,386,041,000	3.1	0.03 kg VS	0.30 – 0.34 m^3 CH_4	2.34 - 2.65·10^5 m^3 CH_4/day
			Day · 1000 kg animal mass	kg-VS	
Swine	59,931,800	59.0	8.5 kg VS	0.36 – 0.47 m^3 CH_4	10.8 - 14.1·10^6 m^3 CH_4/day
			Day · 1000 kg animal mass	kg-VS	
Total Potential Methane Production from Livestock per Day					**134.03·10^6 m^3 CH_4/day**

* Safely et al., 1992; USDA, 2001.

Table 2: Production of Municipal Solid Waste and Potential Methane Production in the USA.

Waste Type	Thousand Tons generated per year	Metric Tons generated per year	Total Solids, %	Volatile Solids (% of TS)	Maximum Methane Production Capacity, B_o m^3 CH_4/-VS	Methane Produced per Kg dry biomass m^3 CH_4/MT biomass
Newspaper	13,490	12264	92.2	97.6	0.100	1104
Books	1,120	1018				
Magazines	2,160	1964	97.1	78.1	0.203	302
Office paper	7,000	6364			0.369	
Directories	470	427				
Standard (A) Mail (3rd class)	4,850	4409				
Tissue paper/towels	3,100	2818			0.360	
Disposable diapers	3,140	2855				
Corrugated Boxes	30,160	27418	94.8	92.7	0.278	6698
Milk Cartons	460	418			0.318	
Folding cartons, packaging	5640	5127			0.334	
Wrapping paper	50	45			0.341	
Wood packaging	7,030	6391			0.22 to 0.32 (hardwoods) 0.01 to 0.06 (softwoods)	
Food Wastes	21,910					
Mixed Yard Trimmings	27,730		50.4	92	0.140	1800
Cellulose, theoretical yield					0.375	

Owens and Chynoweth, 1993; U.S. EPA, 1999

end products. For example, the total amount of methane that is generated from animal waste is estimated to be $134.03 \cdot 10^6$ m^3 CH_4/day, which indicates that if methane were produced by anaerobic digestion of all biomass waste, the amount of methane would be equal to at least half of the current demand of natural gas in the USA today. At the same time, the very serious problem of disposal of this biomass would be eliminated- any residual solids from anaerobic digestion are odorless and may be used for compost, fertilizer or soil conditioner.

Although the process of producing methane from "waste" biomass materials has been known for over a century (Gijzen, 2002), the cost of techniques for using this process have been considered to be too expensive and not economically competitive with the price of natural gas. Most current anaerobic digestion designs involve expensive tanks and other equipment including stirring and heating and scrubbing the gas (such as many of those currently operating in Germany, Weiland, 2000). Because of the costs involved, production of methane from biomass has continued to be an underutilized process for generating renewable energy. Therefore, detailed research and analysis on more economical systems is greatly needed. A successful system will be simple and inexpensive- with no stirring, heating or need for scrubbing the methane gas—and will be capable of use on a very small scale or a very large scale by individuals or by large industries. This paper describes and explains such a system and the development of optimal design criteria.

Recently, Oswald (1996 and 1994) and others (Chynoweth et al., 2001) have demonstrated that inexpensive techniques do exist for producing methane. These processes are carried out anaerobically in deep lagoons (about 25 feet deep), which have been shown to be capable of greatly reducing the emission of other polluting gases, such as carbon dioxide, hydrogen sulfide, and phosphine. Methane is highly insoluble in water in comparison to these gases, and the depth of the pond provides a means of scrubbing out more soluble gases. These systems are not mixed (i.e., mixing is naturally provided by the bubbling gas or natural fluid flow by gravity) or heated, and the depth additionally allows for a long retention time to replace the need for these excess energy requirements. Unfortunately, such inexpensive techniques are not well known among engineering, agricultural, landfill and waste-management professionals, and they are even less well known among the general public.

These emerging and underutilized techniques for: (1) disposing of the vast amounts of biomass waste being continuously generated, and (2) at the same time producing a highly valuable source of renewable energy (methane), have enormous potential for commercialization. Individual operators, such as farmers, food-processing plants, landfills and cities are able to build and operate units of the appropriate size and amortize the plant economically in 3 to 5 years from the use or sale of the methane. In contrast to the high cost of especially prepared biomass (such as agricultural crops, i.e. corn for ethanol) for producing renewable energy, the cost of using biomass wastes is virtually zero or even negative because it can dramatically reduce the present costs associated with disposal. Additionally, methane may be used as the source material for hydrogen production by further processing (Lay et al. 1999). Hydrogen is the high priority pollution-free fuel of the future (hydrogen combustion produces only water as a byproduct for vehicles and mobile units). Hydrogen may be produced from methane by steam reformation or by pyrolysis—which converts the carbon to carbon black instead of carbon dioxide. The methane or hydrogen produced can be used as fuel for vehicles operating on compressed natural gas (CNG) and can meet virtually any of society's energy needs.

This paper describes and explains a plan to conduct research and development and to provide a demonstration of the profitably of disposing of various types of agricultural wastes and other biomass wastes that are such a serious problem at the present time. It also explains a plan to prepare and present the information, through workshops and educational materials, to engineers, waste management professionals, students, farmers and the general public so that the two problems may be mitigated simultaneously.

Technical Aspects

This project consists of an anaerobic, deep digestion tank that is used as a digestion chamber for the digestion of various types of biomass wastes and specially designed to produce methane and to neutralize and reduce the volume of solids. The methane is used to operate electrical generators, to produce heat or to replace or supplement natural gas or sold to a natural gas pipeline. The residual solids are used as compost, fertilizer and/or a soil conditioner as appropriate. The effluent is used for irrigation of crops or treated so that it can be returned to groundwater or put in natural streams.

Objectives

The following are the objectives of this project:

- To demonstrate the effectiveness of the deep digester tank as a cost-effective means of waste-minimization and energy production.
- To develop design criteria for optimal performance of the digester lagoon.
- To disseminate knowledge about the benefits of anaerobic digestion of biomass to farmers, industry, and the public through education and outreach.

The stated objectives are to be met by completing the following tasks:

1. Construction, operation and maintenance of the deep digester pond and the receiver pond for the effluent from the digester pond.
2. Selecting and procuring the different biomass wastes, and combination of wastes, to be digested.
3. Setting up a schedule and procedure for periodic and systematic testing, laboratory analysis and concluding results for the operation and functioning of the system and the productive use of the products.
4. Carrying out the tests for a variety of biomass materials and combinations of materials formation of database for pond biomass digestion research.
5. Utilizing the gas, the effluent and the residuals from the digester tank.
6. Developing the economics and business aspects of deep digester tank.
7. Preparing written materials web pages/sites and presenting educational workshops for the benefit of a wide variety of stakeholders.
8. Preparing business plans for various sizes of digesters and various combinations of biomass.
9. Educating students and engineering and other professionals about the benefits of anaerobic digestion.

Deep Digester Design and Operation

The digester is a used truck petroleum transport tank 8 feet in diameter and 40 feet long which is placed vertically so that the top of the tank is 40 feet higher than the bottom. Additional tanks are added as needed. Separate tanks and a compressor will temporarily store the methane until it is used in an engine/generator, burned to produce heat or used to replace or supplement the supply of natural gas.

The technical use of the vertical digester tank is to digest various kinds and combinations of biomass wastes. This includes biomass wastes from: dairy cattle, a meat packing plant, a landfill and other organic wastes. The wastes are introduced into the tank in influent water through a pipe 15 feet above the bottom of the tank. The inflow is directed downward to cause the solids to accumulate at the bottom of the tank where they are digested and then easily removed to make compost.

The bench work research in the laboratory by Chynoweth and others has shown that, once the anaerobic bacteria are well established, most of the methane-producing digestion is completed in about a month. Testing is done at various points in the digester tank on a regular basis of weekly sampling. Testing will be at nine points, which are the center points and the quarter points of the tank. This includes a vertical profile of testing the gas, the liquid and the solids by sampling for laboratory analysis. The influent and the effluent is also tested. The residual solids are tested for composition.

The data collected are gathered and documented as follows:

1. A series of technical papers that can be published in technical journals.
2. Papers are to be presented at technical and professional meetings.
3. Information documents and databases are to be prepared for the press and publicity.
4. Also to be prepared are detailed instructions, guides, and standards of procedure for the use of city, county and state officials, and industries, which are charged with disposal of biomass waste.
5. Information, guides and training materials are to be prepared for farmers, ranchers and others for disposal of organic wastes to produce distributed energy.
6. Hand-out and instructional materials and web sites for seminars, short-courses and high school and university courses are to be prepared on the anaerobic digestion of biomass wastes.

Analytical Methods

The Hydrolab probe is a cutting-edge product produced by Hach, Inc. of Loveland, Colorado. The major advantage of the Hydrolab probe, for this digester, is its capability for *in situ* measurements. The probe is used to obtain the following in situ data from the tank: DO, pH, sulfates, nitrates, conductivity, turbidity, total dissolved gas, ammonia, chloride, ORP, and temperature. These are determined on a weekly basis at the 9 sampling points with varying depth.

Certain critical measurements cannot be measured in situ (such as solids analysis, digestion, or other analyses which require physico/chemical transformation of the sample) and therefore are carried out in the laboratory. These are described in Table 3. Samples are collected from the digester tank at varying depths from the 9 sampling points, placed on ice, and immediately transported to the laboratory for analysis

Table 3: Analyses Performed on Digester Tank.

Data/sample	**Frequency**	**Method**	**Equipment**
LIQUID PHASE			
TSS	Weekly	Ehrman, 1994	105º C /550º C ovens
VSS	Weekly	Ehrman, 1994	105º C /550º C ovens
Inorganic Carbon (IC)	Weekly	Manufacturer's Instruction	Rosemont Dohrmann TOC analyzer
TKN	Weekly	EPA Standard Methods	Hach Digester
COD	Weekly	Manufacturer's Instruction	Hach Digester
SO_4	Weekly	Manufacturer's Instruction	Dionex Ion Chromatography
Sludge composition (lignin, cellulose, cellobiose, ash…)	Monthly	Ruiz and Ehrman. 1996b, Ehrman 1994, Ruiz and Ehrman, 1996	Hach Digester, HPLC
Soluble lignin	Monthly	Templeton and Ehrman, 1995, Ehrman, 1996	HPLC
Organic acids	Monthly	Pullammanappallil et al., 1998	HPLC, BioRad Organic acid column
S^{2-}	Monthly		Sulfide probe
Bacterial Community (DGGE)	Monthly	Muyzer et al., 1993, Liu et al., 2002	BioRad DCode Mutation Detection System
Active Biomass (Phosphlipids)	Monthly	Findlay et al., 1989	HP 6150 UV/vis diode-array spectrophotometer
GAS PHASE			
CH_4, CO_2, N_2, NO, H_2S, H_2	Weekly	Kelly and Chynoweth, 1981	HP 6890 GC/TCD

Microbial Community Analysis

The characteristics and evolution over time of the digester microbial community is determined using denaturing gradient gel electrophoresis (DGGE) of polymerase chain reaction (PCR) amplified fragments of the community 16S ribosomal DNA. DGGE is a powerful method of profiling microbial communities, and is especially useful for comparative studies and high sample throughput (Muyzer et al., 1993). This analysis takes place once per month with samples taken throughout the digester breadth and depth. The main purpose is to identify key microorganisms present within the community with respect to the different kinds of biomass applied. Of particular interest is the relative abundance of cellulose and lignin degraders, as correlated with observed degradation of these compounds and the extent of methanogenesis. These compounds often form the bulk of undigested material remaining in the sludge. Methanogenic microbes (belonging to the Archaea), the ultimate methane producers, are also monitored by DGGE. Gaining a better understanding of microbial communities in the digester lagoons is an important path to consider in improving design and performance of this biologically-catalyzed system. For example, Abou et al. (2003) found the composition of the microbial fractions to be highly determinant in digester performance, especially in psychrophillic (sub-ambient) digesters, which are operated without heating, such as the system described and explained in this paper.

Expected Results and Benefits

The world population is currently growing at an exponential rate, and concurrently so is the waste production associated with human activity (domestic, industrial, and agricultural). At the same time, energy resources are diminishing at a similarly rapid pace. It is impossible to overstate the imperative need for human society to find sustainable means of energy production which are in harmony with human health and the environment. Conversion of organic waste to energy is clearly a most attractive option for mitigating this problem. This is especially true with respect to the millions of tons of waste biomass which are constantly being produced in the U.S. and around the world. The choice is clear: either allow this waste biomass to continue polluting the environment (whether from pathogens, or uncontrolled methane and carbon dioxide production which contributes to global warming) and continue to deplete the remaining reserves of fossil fuels, or take the initiative to begin converting this waste biomass into energy.

The purpose of this paper is to play a leading role in moving towards a sustainable society. While converting waste into energy is especially appealing conceptually, there are still much needed advances before this technology becomes common place. Research is necessary in order to optimize these technologies, to build confidence in their effectiveness, and to prepare them for market. This will require not only basic research, analysis, and modeling- but importantly, significant efforts in outreach. Farmers, engineers, business people, and the community must be made aware of the issue of sustainable development which stands before us, and the promise that anaerobic digestion holds for meeting this need. This paper, therefore, incorporates both the basic research and development and education and outreach that will be critical in order to take this step towards attaining a sustainable society.

Conclusions

In terms of deliverables, it is expected that the results of this project will yield:

- A demonstrated low-cost system for converting waste biomass into methane.
- Optimization criteria for system operation with respect to various waste biomass influent.
- A market-ready sustainable energy technology
- An environmentally-friendly means of biomass waste minimization with production of a beneficial end-product (soil conditioner)

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