anaerobic digestion of solid waste and sewage sludge to methane

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ANAEROBIC DIGESTION OF SOLID WASTE AND SEWAGE SLUDGE TO METHANE

By Steven J. Hitte*

Objectives

The primary objective of this report is to evaluate the potential for processing organic wastes (solid waste and sewage sludge) using a controlled anaerobic digestion process for the purpose of producing methane. Controlled anaerobic digestion is a biological process whereby organic matter decomposes in a regulated oxygen-deficient environment. This report is intended: (1) to present a way in which the national energy shortage can be reduced by producing methane from anaerobic digestion of municipal solid waste and sewage sludge; (2) to compare and describe this biological process with other resource recovery concepts; (3) to summarize the current research being performed in anaerobic digestion; (4) to present an estimated cost analysis of a 1,000-ton-per-day (TPD) solid waste and sludge digestion facility.

Energy Demand

Anaerobic digestion for the conversion of waste materials to methane is one possible means to offset the increasing shortage of natural gas. The total United States energy demand in 1972 was approximately 72 quadrillion (10^{15}) Btu and is projected to exceed 96 quadrillion Btu by 1980. Natural gas (methane) supplies 32 percent of this total energy demand (23 quadrillion Btu).[1,p.2] Yet the nation's reserves of energy, particularly natural gas, will be able to provide only a decreasing fraction of projected energy supplies. New developments in technology can help to develop new supplies of energy. Production of natural gas through anaerobic digestion of solid waste and sewage sludge is one such new technology that can increase the nation's supply of energy.

Potential Market

The potential market for a process which converts solid waste and sludge to methane is significant. There is a potential market for over 200 1,000-TPD solid-waste and sludge-to-methane facilities

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* Mr. Hitte is a mechanical engineer in the Systems Management Division of EPA's Office of Solid Waste Management Programs.

in the urban areas of the United States. With the current municipal solid waste generation rate of 3 to 5 pounds per person per day and a sewage sludge generation rate of 0.3 to 0.5 pounds per person per day, a population of approximately 500,000 could provide enough waste to supply one 1,000-TPD facility. According to the 1970 United States Census, there were 26 cities in the country with populations in excess of one-half million. More significantly, there are 65 Standard Metropolitan Statistical Areas (SMSAs) in the United States with populations in excess of 500,000. The aggregate population of these SMSAs is in excess of 100 million, half of the nation's population.

Bioconversion of solid waste and sewage sludge is one energy conversion option. Based on data from bench-scale experiments, a 1,000-TPD bioconversion facility could produce approximately 3.6 million cubic feet of methane per day based on a conservative value of 1.8 cubic feet of methane generated per pound of municipal solid waste and sewage sludge.[2,p.82] The 65 SMSAs with populations in excess of 500,000 therefore have a potential for methane production in excess of 720 million cubic feet per day. Based on figures published in the 1973 edition of Browns Directory of North American Gas Companies, this process, if implemented in those 65 SMSAs, could supply a small, supplementary percentage of the total natural gas consumed in the United States. In addition, animal, crop, and some industrial wastes represent the potential of an additional 13 billion cubic feet per day of methane (20 percent of the natural gas demand), although the economics of collection and transportation may restrict their use.[3,p.7] These wastes are not considered to be a viable potential for purposes of this paper.

On a local basis, natural gas produced from municipal solid waste can supply higher percentages of total gas consumption. For example, if all the waste in the Cleveland SMSA (Cuyahoga County) (1970 population: 2,064,000) could be utilized, 5.3 billion cubic feet per year of methane could be produced, approximately 2.8 percent of Cleveland's natural gas demands.*

These projections show that methane produced from solid waste can contribute as a supplemental source of energy. This comes at a time when energy shortages and rising solid waste disposal costs are forcing many major communities to reevaluate their refuse disposal practices.

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* The natural gas sales volume of the Cleveland Division of the East Ohio Gas Company in 1973 was 190 billion cubic feet. The population of Cleveland in 1970 was 751,000. The potential for gas production from wastes in the City of Cleveland is 1.9 billion cubic feet per year, approximately 1 percent of Cleveland's natural gas demands.[2,p.126]

Energy Products from Resource Recovery Concepts

Municipal solid waste is one raw material currently being discarded that can be "mined" for its energy content. Presently, many different approaches to recovering this energy are being examined. Included in these resource recovery concepts are: (1) shredded and classified solid waste as a supplemental fuel, (2) pyrolysis, (3) waterwall incineration, (4) hydrogasification, (5) methane production. All of these technologies enable solid waste to be converted into a number of energy forms, including solid, liquid, and gaseous fuels, and steam and electricity; they also offer the opportunity of front-end recovery of valuable materials.

To be marketable, these energy products must be produced at a cost competitive with the fossil fuels they supplement or replace. This cost is indirectly related to the energy recovery yield of the system. The equation for this yield is as follows:

$$E_{RY} = \frac{E_o - E_c}{E_A}$$

Where E_{RY} = percent of energy recovery yield
E_o = usable energy out of the system measured in Btu
E_c = total energy consumed by the system, measured in Btu
E_A = energy available in solid waste based on 4,500 Btu/pound of waste

For most of these systems, the energy recovery yield ranges from 20 to 30 percent.

Anaerobic digestion is the only known process that produces an energy form (methane gas) in large quantities that can be used directly by the consumer for home heating, cooking, and other such purposes.* When the gas produced is cleansed to pipeline quality (1,000 Btu per cubic foot), it could be easily marketed because it can be injected directly into a local utility pipeline system. The indications from a telephone survey are that utilities are very positive about purchasing even small quantities of this high Btu gas, as long as the price is competitive with other sources of gas.

Current Research

Presently, there are a number of groups studying the bioconversion process. Dr. Perry McCarty, Stanford University, and Dr. Clarence Goluecke, University of California in Berkeley, are two such researchers

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* All other energy recovery processes require conversion to steam or electricity.

who have performed studies in bioconversion of organic waste to methane. Much of their work has been published in scientific journals and proceedings from various conferences.[4,p.1,58] Dr. John Pfeffer, University of Illinois, has also done substantial research in the temperature ranges and the various dewatering processes to increase the efficiency of this process. The Dynatech Corporation, Cambridge, Massachusetts, has concluded a paper study on the economics of the anaerobic digestion process. Computer models were designed to incorporate all parameters of this process to determine the economy of scale.[2,p.11]

In Franklin, Ohio, research work is underway to investigate the feasibility of combining solid waste with sewage sludge, having the mixture digested and capturing the energy value through the production of methane for use as a fuel. In this process, wet-processing may be advantageous because small particle sizes and large quantities of water are needed to create optimum conditions for decomposition. This work is being done in conjunction with a project funded formerly by EPA with the Black Clawson Company.[5]

Dr. S. Ghosh and Dr. D. Klass, Institute of Gas Technology, have performed various experiments on varying the particle size of the solid waste fed into a digester to increase gas production. Their findings indicate that the finer the particle size, the higher the gas yield.[3,p.7]

The engineering department at the University of Arizona has performed bench-scale work (100 gallons) on digesting combined raw sewage and solid waste. Scaled-up work for a 20,000 gallon in-ground digester heated by solar energy has recently been completed. The cleaned methane will be used for local needs with the remaining CO_2 supporting a greenhouse and the residue acting as a soil conditioner.[6]

In the summer of 1975, the Energy Research and Development Administration (ERDA) awarded a multimillion dollar contract to construct and demonstrate the feasibility of producing methane gas from the solid waste stream. This will be a four-year study incorporating a design capacity of 50 to 100 TPD.

Other industries and universities are studying this process and dispersing their findings through conferences and publications. With all this interest in waste digestion, the near future might provide some sound conclusions and technology on whether this process is viable.

Biological Process

Anaerobic digestion of complex organic wastes is a two-stage process (Figure 1). In the first stage, the acid-forming bacteria act upon complex organics and change the form of complex fats, proteins, and carbohydrates to simple soluble organic materials, commonly known as organic or volatile acids. The second stage involves the fermentation or gas-generation phase which produces the desired methane gas. In this step, the methane-forming bacteria use the organic acids produced in the first stage as substrate and produce the end products: carbon dioxide (CO_2), methane (CH_4) and traces of hydrogen sulfide (H_2S). The quantities of these off-gases can vary but the mixture consists of roughly 50 percent CO_2 and 50 percent CH_4.

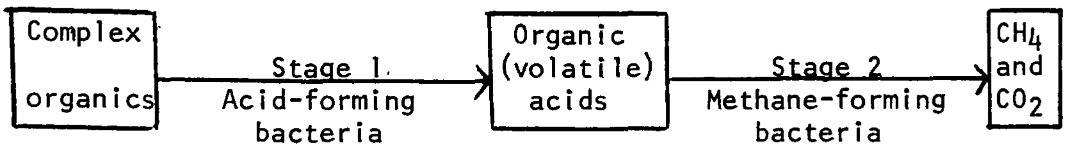

Figure 1. This diagram illustrates anaerobic digestion of complex organics, which are defined as large molecular chain structures containing carbon, hydrogen, glucose, cellulose, etc.

Parameters Controlling Methane Production

To attain continuous digestion, a proper balance between the acid-forming bacteria and the methane-forming bacteria is required. Optimum levels of five environmental parameters are essential to the establishment and maintenance of this balance; these parameters are: temperature, anaerobisis, pH, nutrients, and toxicity of input.

Temperature is an important operational parameter in an anaerobic digestion process. As temperature increases, biological reactions proceed much faster, and this results in more efficient operation and lower retention-time requirements which may vary from 4 to 30 days. Two temperature levels have been established: in the mesophilic level, the temperatures range from 30 to 45°C; in the thermophilic level they range from 45 to 60°C. Although rates of reaction in the thermophilic level are much faster due to increased bacteria formation than those in the mesophilic level, the economics of most sewage sludge digestion systems have indicated operation in the mesophilic level.*

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* Much controversy over the temperature levels has been voiced by various researchers. The debate is over the efficiency and economy of operating a digester at these temperature levels. Some bench-scale experiments have been performed varying the temperature and monitoring the gas produced with the retention time, but results are not consistent and may not be applicable to a full-scale system.

Another environmental requirement for anaerobic digestion is the maintenance of anaerobic conditions (anaerobisis) in the digester. The methane formers are strict anaerobes and even small amounts of oxygen can be quite detrimental to them. This necessitates a closed digestion tank which excludes oxygen while also facilitating collection of the methane produced.

The third environmental requirement for optimum operation is proper pH control. Anaerobic digestion can proceed quite well under slightly acidic conditions, with a pH varying from 6.7 to 7.0.[7,p.11] Beyond these limits, anaerobic digestion proceeds with decreasing efficiency. Under more acidic conditions, a pH of 6.2 or lower, waste stabilization ceases. Control of pH is exercised by the addition of an alkali [sodium bicarbonate ($Na(CO_2)_2$)], which has recently been found to control pH better than lime.

The bacteria responsible for waste fermentation in the anaerobic process require nitrogen, phosphorus, and other materials for optimum growth. Therefore, another important environmental condition is the presence of the required nutrients in adequate quantities. These nutrients are measured against a carbon-nitrogen (C-N) ratio. The C-N ratio of solid waste is not sufficient for maximum digestion, hence the addition of sewage sludge, which adds nitrogen to create a more favorable ratio, is necessary.

For successful anaerobic treatment, the fifth environmental parameter, that of toxicity of input, must be at the level where the waste is free from toxic materials. These inhibitory materials range from inorganic salts to toxic organic compounds. Control of toxicity can be achieved by removal of toxic materials by chemical precipitation within the digester and by dilution of the waste stream below the toxic threshold of the toxicity-causing material by such means as increasing the moisture content of the slurry.

Once these five parameters have been established and maintained at their optimum levels, then production of gas should occur naturally. The methane remaining after gas cleansing has a heating value of 1,000 Btu per cubic foot. This is pipeline quality and acceptable from a gas company's viewpoint.

Process Description (Conceptual Discussion)

As devised by the researchers on their bench-scale experiments, the physical apparatus for producing methane gas from municipal solid waste and sewage sludge could be divided into four areas of operation (Figure 2): (1) waste handling and mixing, (2) digestion, (3) gas treatment, (4) effluent disposal.

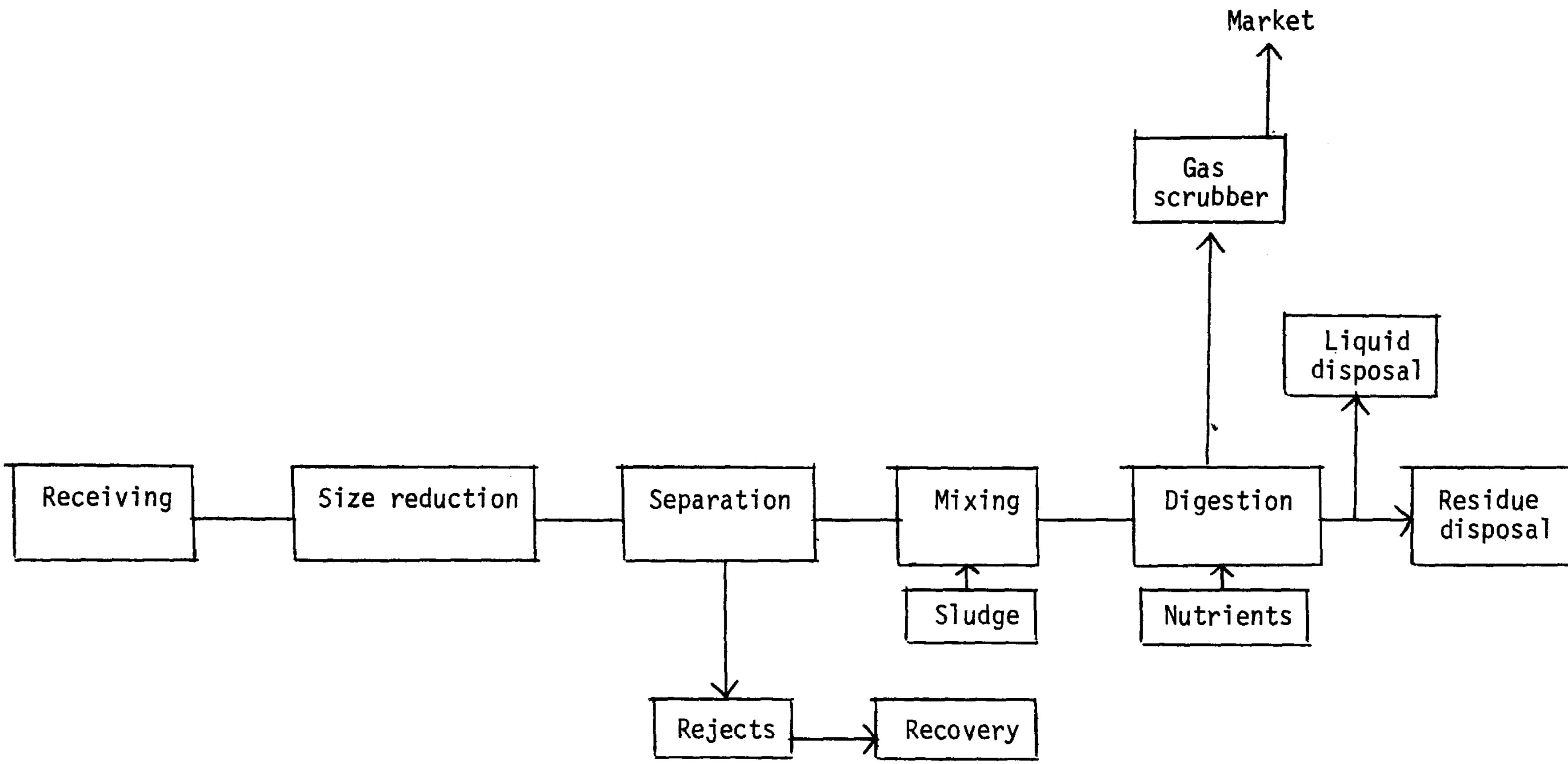

Figure 2: This diagram shows areas of operation in the anaerobic digestion of municipal solid waste and sewage sludge.

The municipal solid waste, after being deposited on the tipping floor, would be shredded for ease in materials handling. The shredding operation would fulfill two primary functions: it would allow for efficient separation of the organic material from the inorganic, nondigestible matter (metal cans, bottles, etc.) found in municipal waste; and it would reduce the feed to a homogeneous size, which would be more readily digested.

Separation systems based on two different principles are currently being developed; these are the dry and wet separation processes. The dry separation process is being demonstrated in St. Louis and the wet separation process in the City of Franklin, Ohio.[8,5] Both processes provide a waste stream with a high concentration of organic matter relatively free of metals, glass, and grit. In a dry separation process, the shredded material is air classified during which the organic materials are separated and recovered as the lighter fraction. The light organic material then would be shredded in a secondary shredder and conveyed pneumatically to a storage silo where it would be finally ready for digestion. In the wet system, the shredded waste would be fed into a hydropulper to be mixed with a large amount of water. This process is similar to that of a kitchen sink disposal unit. Fibrous materials are recovered as a dilute aqueous stream which would be conveyed pneumatically to a storage silo where it would be finally ready for digestion.

Before the waste material enters the digester, it must be mixed with nutrients (sewage sludge) and other chemicals (lime, sodium bicarbonate, phosphorus) necessary for the digester operation. At this stage, animal or agricultural wastes could be blended into the slurry if these were part of a locality's waste stream. Each digester would be maintained at constant pressure and temperature and would be provided with a means for continuously stirring the contents.* Stirring allows uniform digestion of the material to proceed in two stages as described in a previous section. The products of digestion consist of two streams. One stream would be composed of methane and carbon dioxide in equal volumes, and the other would be residue that must be disposed of appropriately.

The methane produced from the digester would contain carbon dioxide and traces of hydrogen sulfide. These two acid gases must be removed before the methane is sold. This could be accomplished via one of a number of gas-cleansing processes. These are the molecular sieve, Selexol,+ and diglycolamine processes. All three systems are designed to remove large concentrations of carbon dioxide (50 percent for digester gas).[9]

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* Ten 60,000 cubic feet digesters would be needed for a 1,000-TPD plant.

+ Selexol is a registered trademark of Allied Chemical Corporation.

The final operation, the effluent disposal, would be best carried out by separating the solids from the liquid and returning the liquid to the sewage treatment plant for subsequent treatment and final discharge. The solids, in the form of the moist sludge obtained from various dewatering processes such as vacuum filtration, centrifuging, and heat drying, could then be disposed of or utilized. Various methods could be used: incineration, landfilling, use as a soil conditioner, reclamation of strip mines, or compression to form fiberboard. This sludge, whose volume would be only 20 percent of the incoming solid waste, would have a heating value of 4,000 Btu per pound (25 percent solid) and could be burned to generate usable steam.

Benefits

The potential benefits resulting from the anaerobic digestion of solid waste are: (1) energy recovery in the form of methane gas to be used directly in home heating and cooking, (2) reduction of the municipal solid waste disposal problem on a large scale, (3) reduction of the sewage sludge disposal problem, (4) materials recovery from the sale of ferrous metals and other secondary materials (Figure 3).

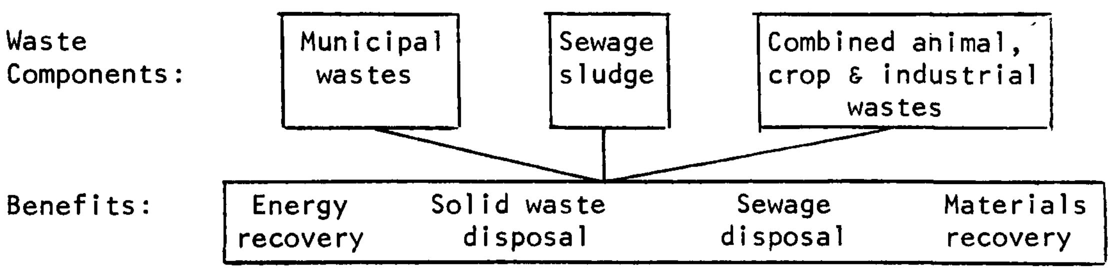

Figure 3. A simplified block diagram illustrates the waste stream components and associated benefits resulting from the anaerobic digestion of organic materials.

Projected Economics of a Conceptual System

The economics of an anaerobic digester plant can only be estimated since the process has not been demonstrated on a full scale (1,000 TPD). The following capital and operating costs are based on a study done in July 1974 by the Dynatech Corporation, Cambridge, Massachusetts.[2,p.81] Annual capital cost figures are based on typical 20-year, 6-percent financing. It would not be advisable to assume that these figures are automatically applicable to all parts of the United States without a prior study of pertinent factors such as site costs, labor and material costs, product marketability, plant size, etc.

The capital and operating costs per ton and revenues per ton of the plant for a 1,000-TPD plant, processing wastes 310 days per year, producing gas 365 days per year have been projected (Table 1). If a municipality pays $13 per ton or more to dispose of its solid waste and sewage sludge, serious consideration should be given to implementation of the anerobic digestion process should full-scale systems be proven technically feasible.

TABLE 1

PROJECTED ECONOMICS OF 1,000-TPD BIOCONVERSION PLANT

Costs	Costs/Ton
Capital including amortization*	$ 3.60
Operating+	7.10
Residue disposal‡	2.30
Total	$13.00
Revenues	**Revenues/Ton**
Sale of natural gas§	$3.60
Sale of ferrous metal¶	2.70
Credit for sludge disposal**	1.90
Total	$8.20

* Plant cost: $22 million, 20 years, 6 percent municipal bonds; includes design, site, equipment, and construction costs.

+ Includes supplies, chemicals, maintenance, utilities, labor overhead, taxes; no detailed breakdown is available.

‡ Sanitary landfill (SLF) at $5 per ton of digester residue, heavies from air classifier, and waste water.

§ Sell at $1 per mcf ($1/MMBtu).

¶ Sell at $40 per ton.

** SLF at $5 per ton.

Environmental Impact

The greatest advantage of an anaerobic digestion system is its positive environmental impact. Solid waste which would normally be disposed of in a land disposal site can now be converted into a useful product (gas) with no adverse impact on the environment. Because of the absence of air pollutants and with proper control of the effluent and residue, there will be no adverse environmental effect from the operation of such a solid waste conversion plant. The positive contributions of this system in the elimination of the land disposal of wastes and in the recovery of valuable materials and fuel make this an environmentally desirable approach to solid waste management.

Disadvantages

Because anaerobic digestion of waste materials has not been demonstrated on a large scale, there is considerable risk that the system will not perform as predicted. The potential exists that the digesters will sour from time to time. This potential is supported by the experience of operating sewage sludge digesters where the biological process occasionally is inhibited. The addition of air-classified organic solid waste to sewage sludge in a digester should maintain the proper chemical balance so as not to inhibit this biological decomposition of the waste materials. As other resource recovery concepts, the process is also capital-cost intensive. Other drawbacks are that it initially has relatively low gasification rates over a period of time (retention time in days) as compared to other resource recovery concepts and that the construction of a 1,000-TPD plant would cover significant acreage (12 acres) if land was at a premium. If a full-scale system was implemented, almost all of these disadvantages could be overcome by experience.

Summary

In summary, the anaerobic digestion process if developed to applicable technology stages could:

- maximize the conversion of municipal solid waste and sewage sludge into a usable fuel;
- facilitate recovery of materials;
- handle other wastes mixed with the municipal solid waste and sewage sludge such as animal, crop, and some industrial wastes;
- operate without causing pollution to the air.

So far, the only drawback to implementing an anaerobic digestion system for a community is the initial capital investment to construct such a facility. The existing technology for the various system components such as the shredder, digestion tank, and gas cleansing unit are available and operating today but all these components must still be joined together into a fluent, functioning system for solid waste and sewage sludge. Until this is done, the anaerobic digestion process will remain dormant.

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