

**Anaerobic Digestion Technology:
The Central Element**

The following is a “pre-print” of an article scheduled for publication in April or May 2010 in Microbe, the peer-reviewed general interest online magazine of the American Society of Microbiology.

(<http://www.microbemagazine.org/>)

On publication, a direct link to the article will be provided. The article comparatively analyses five different forms of anaerobic digestion for their suitability in the treatment of solid waste. Their conformance or non-conformance to the scientific understanding of microbial methanogenesis is emphasized. The figures will be finalized by ASM’s editorial staff.

Suitability of Anaerobic Digestion Variants for the Treatment of Municipal Solid Waste

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Anaerobic digestion, the exploitation of microbial methanogenesis for economic purposes, is in its infancy as a solid waste management tool. To contribute significantly to resolving solid waste problems, which are legion, exclusively empirical approaches to reactor design and control must be replaced with rational ones.

Author profile. His goal is to narrow the gap between solid waste practice and microbiological science.

Municipal Solid Waste: A Problematic Mixture

The United States Environmental Protection Agency defines municipal solid waste (MSW) as “everyday items such as product packaging, grass clippings (yard trimmings), furniture, clothing, bottles, food scraps, newspapers (paper and paperboard), appliances, and batteries.” Almost three fourths of the 254 million tons of MSW generated in 2007 was, in principle, biodegradable (paper, yard trimmings, food, wood, natural textiles, rubber and leather). But as a practical matter, only up to one-third of the total (85 million tons) would have been amenable to anaerobic digestion, had this fraction been isolated from the overall waste mixture. Target materials include food waste (13% of the total), yard trimmings (13% of the total, half of which is excluded from consideration in being composted in backyard gardens or in technologically simple and inexpensive community facilities), and paper products (33% of the total, over half of which is excluded as being recovered as secondary commodities through recycling programs). These statistics, though showing the “big picture,” mask the extreme truck-load by truck-load heterogeneity and variability of MSW, and the difficulty of fractionation (Figure 1).



Figure 1a. An example of what an MSW collection truck might deliver to a disposal facility.

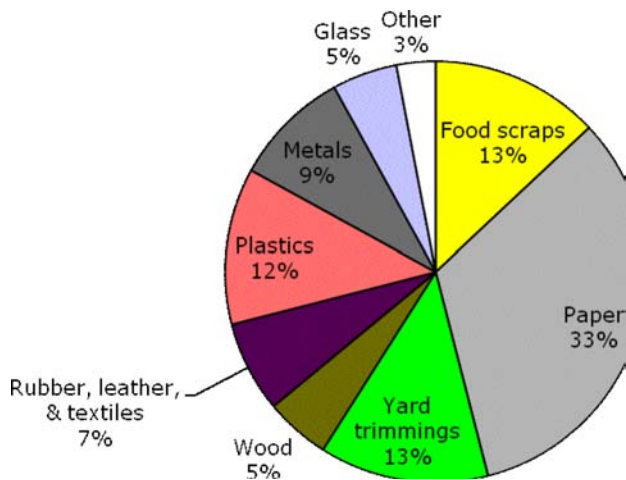


Figure 1b. Broad categories of MSW generated in 2007 as reported by US EPA.

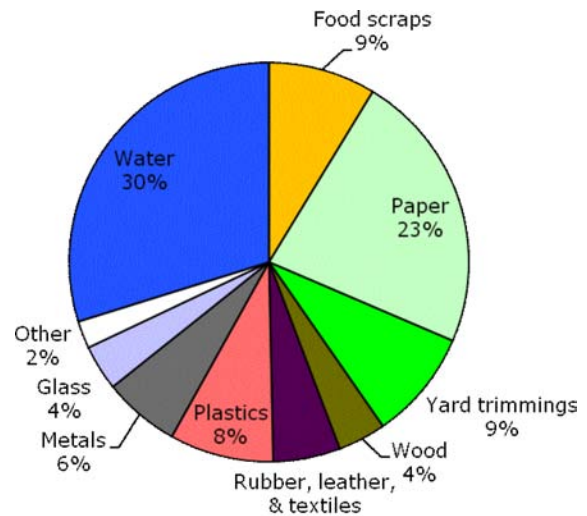


Figure 1c. Panel 1b adjusted for “nominal” moisture content. Moisture content, though rarely determined, is highly variable, and significantly affects all stages of handling and processing.

Even voluntary and mandated food waste source-separation programs, currently focused on composting but potentially shifting to anaerobic digestion, yield mixtures containing non-compliance items needing to be removed before biological processing. Thus solid wastes arise as complex mixtures and, notwithstanding the term, an “anaerobic digestion facility” actually consists of three major elements:

1. pre-digestion to recover recyclable materials (paper, plastic, metal, glass), to remove non-processible inclusions for disposal in the landfill (composite products not worth disassembling, non-descript items, stones, sand, “grit”), and to prepare the isolated biodegradables for anaerobic digestion;
2. anaerobic digestion per se to produce methane-containing biogas, digestate (slow to degrade residue potentially usable as “compost”), and water freed from the moisture content of the waste;
3. post-digestion to separate digestate and water, and to condition the biogas for use. Use as boiler fuel or to generate electricity may require the removal of moisture, H₂S, and siloxanes. Injection into the pipeline or conversion to vehicular fuel (compressed or liquefied “natural gas”) requires removal of CO₂.

In France, Germany, and Spain, anaerobic digestion has made small inroads in the management of MSW. In the U.S., a number of cities and counties have sponsored studies to evaluate alternatives to incineration and landfilling (dominant practice). The resultant voluminous reports invariably identify anaerobic digestion as a top contender without, however, consideration of microbial-level design and control and its effect on practical process performance. Rather, technical evaluations concentrate on mechanical aspects. Informed decision-making suffers. No facility has been built.

How well an anaerobic digestion system performs is determined by the rate and extent of degradation, reflected in the amount of biogas produced and its methane content, and the amount of residual digestate produced and its stability hence readiness for use as compost. The amount of methane produced is inversely related to that of digestate, whereas the amount of methane is directly related to digestate stability. Similarly determined by rate and extent are factors such as the odor prevention, facility area (“footprint”), reactor height (important aesthetic consideration), economic feasibility, public acceptability, and, not least of all, the costs of construction and operation. Much depends, ultimately, on how the responsible microbes are managed.

Anaerobic digestion has a long history of use in the treatment of sewage sludge, but process design and control is stubbornly empirical and tradition-bound. Moreover, owing to pilot programs in which food waste is being injected into sewage digesters with excess capacity, outmoded practices may spill over into the solid waste domain.

In contrast, in the treatment of certain “clean” aqueous industrial wastewaters such as from breweries, a generic reactor design and process control strategy consistent with the understanding of microbial methanogenesis is in widespread, successful, use. While not directly applicable to solid wastes or waste streams laden with particulate solids, this generic design served as a model for a technology applicable to these more problematic wastes. This technology is currently in limited use, but has the potential for widespread application to solid wastes. These matters are addressed after a brief digression into microbial methanogenesis in isolation from technological application.

Microbial Methanogenesis: A Snapshot

Methanogenesis is one of the most ancient biological functions on earth, and one of the best understood. A broad range of organisms paves the way for the penultimate and ultimate steps resulting in the generation of methane (Fig. 2).

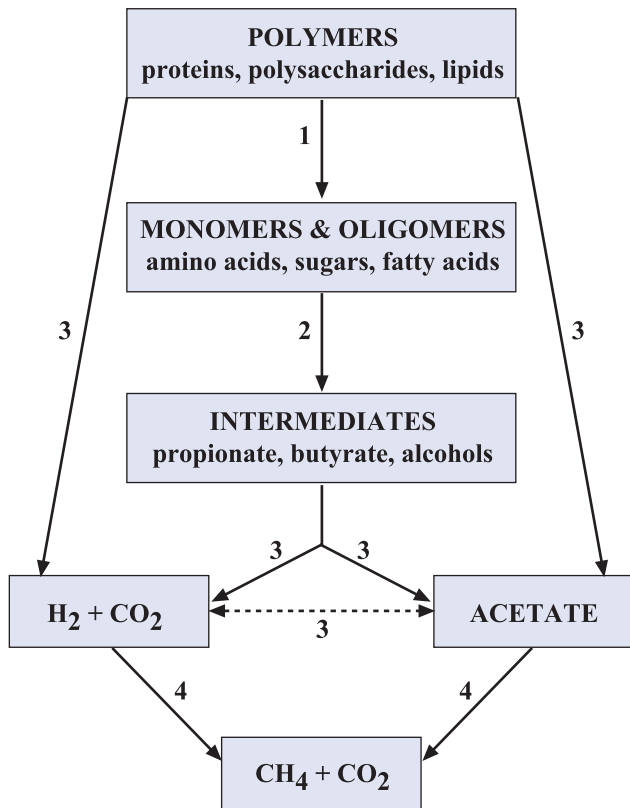


Figure 2. Major pathways leading to the generation of methane. Adapted from L.T. Argent and B.A. Wrenn. 2008. *Optimizing Mixed-Culture Bioprocessing to Convert Waste into Bioenergy. Chapter 15, p. 179-194, in Bioenergy (eds. J.D. Wall, C.S. Harwood, A. Demain) ASM Press, Washington, D.C.* This flow chart was derived, in turn, from earlier reports.

The arrows represent:

1. hydrolysis by a vast and diverse array of Eucarya and Bacteria, principally the latter;
2. fermentation of monomers to volatile fatty acids and alcohols;
3. transformation of intermediates to H_2 , CO_2 , and acetic acid (acetogenesis);
4. formation of methane (methanogenesis) from H_2 and CO_2 or acetate by highly specialized Archaea.

Whereas nature goes about degrading relatively low concentrations of organic carbon compounds at its own relaxed pace, the idea of anaerobic digestion in engineered reactors is to transform concentrated waste as rapidly as possible to methane and residual digestate. The intention is to get “the most bang for the volumetric buck.”

High Rate Anaerobic Digestion in a Nutshell

A few factors go far to explain why certain approaches to reactor design and control can achieve high rates and others cannot. The story has three parts.

The first is that acetogens and/or acidogens (both terms are pertinent) are fast growers, except that some, particularly those that transform butyrate and propionate to H_2 , CO_2 , and acetate are subject to feedback inhibition by the accumulation of H_2 at very low levels. In contrast, methanogens are intrinsically slow growers, and are inhibited by acidic pH values. Thus, to achieve high rates, both the production and consumption of H_2 and acids should be in balance. That is, production should be matched by consumption. Imbalance, with production getting ahead of consumption, creates a bottleneck that reverberates up through the metabolic web, slowing overall degradation.

The second part of the story is encapsulated by three terms: syntrophy (one species consumes the products of another species); interspecies hydrogen transfer (the particular form of syntrophy operative in methanogenesis involving the production and consumption of H_2 and acetate by, respectively, acetogens and methanogens); and consortium (for present purposes, an association of acetogens and methanogens bringing about methane production. The more intimate the association, hence the shorter the diffusive distance between its members, the more efficient the syntrophy).

The story concludes on technological notes. These are that process design and control should promote the development of consortia and protect their integrity (mechanical disruption avoided); that the consortia should be retained within the reactor mainly in the form of an expanded bed or blanket (solid and hydraulic retention times are uncoupled, with $SRT > HRT$); and that the reactor should be fed at a high organic loading rate [chemical oxygen demand (COD) per reactor volume], but not so high as to upset the balance between acidogens and methanogens.

The different parts of this story woven together inform the rational design of systems intended for high rate anaerobic digestion.

Anaerobic Disestion Variants in Reference to the Treatment of Solid Waste

The next task is to examine commercially available approaches for their conformance to the “story” developed above. The context, of course, is the treatment of *solid* waste.

Table 1. Salient Features of Five Anaerobic Digestion Variants*

	UASB	IBR	CSTR	Leach Bed	Tall Silo
Three-phase separator at top of reactor	Passive	Active	n.a.	n.a.	n.a.
Input	Aqueous influent with virtually no particulate solids	Flowable influent with high particulate solids content	Flowable influent with moderate particulate solids content	Solid phase Input	Solid phase Input
Recycle ratio (old/new)	n.a.	n.a.	n.a.	High (2/1)	Very high (6-8/1)
Introduction and transit through reactor	Pumped in, passive upflow through reactor	Pumped in, passive upflow through reactor	Pumped in, completely mixed to keep solids suspended	Wheeled loader	Batches lifted to top via cement pump, gravitational descent
Operational mode	Continuous	Continuous	Continuous	Batch	Successive batches
SRT and HRT	SRT>HRT	SRT>HRT	SRT = HRT	n.a.	n.a.
Thermophilic processing	Feasible	Feasible	Not feasible	Not feasible	Feasible
Fosters development retention of ethanogenic consortia	Yes	Yes	No	No	No
Methane yield relative to potential	High	High	Low	Low	Low
Post digestion composting	Minor operation, if at all	Minor operation, if at all	Major operation	Major operation	Major operation

* UASB is a named but not patented approach. IBR is a patented technology. The others are generic approaches finding various applications.

UASB = upflow anaerobic sludge blanket digestion

IBR = induced blanket (bed) reactor

CSTR = continuously stirred tank reactor

Leach bed = high recycle ratio pile sprinkled with leachate

Tall Silo = vertical structure with very high successive very high recycle ratio batches

SRT = solids retention time

HRT = hydraulic retention time

As seen in Table 1, UASB and IBR have many similarities and some important differences. One difference concerns the means of separating liquid, gas and solid phases at the top of the reactor tank, so as to retain culture within the tank, allow excess water to overflow, and convey gas to storage. UASB's three-phase separator is passive, whereas IBR's is active. Another difference is that IBR is a single stage process with relatively small tanks operated in parallel. In the processing of solid waste though not usually wastewater, UASB is the terminal stage of a two-stage system; it is preceded by an acidogenic stage to solubilize particulates and produce precursors. The other variants need no special preliminary comparison.

UASB digestion. This is a rational technology in the sense that it is based on the science of microbial methanogenesis and is informed by the factors needed to achieve high rate; i.e., it fosters the development and retention of methanogenic consortia. Consortia self-organize into granules only slightly denser than water and form a blanket kept in suspension by the upward flow of influent. UASB was developed specifically for the treatment of strong industrial wastewaters (high COD), such as generated at breweries. Particulates in the influent tend to upset the system through poorly understood mechanisms. In the treatment of solid wastes, the biodegradable fraction must first be converted to a wastewater. This process starts in the pre-digestion element of the facility with extensive mechanical disruption, size reduction, and successive screenings. Subsequent biological processing is in two-stages, in the form of a CSTR acidogenic stage followed by the UASB methanogenic one. Additional screening may be needed between stages, to remove particulates that resisted microbial solubilization. UASB is the gold standard in the wastewater domain, but its application to solid waste is awkward.

IBR digestion. Like UASB, IBR is a rational technology in the sense that it is based on the science of microbial methanogenesis and is informed by the factors needed to achieve high rates; i.e., it fosters the development and retention of methanogenic consortia. IBR was initially developed for the treatment of dairy manure flush water laden with particulate solids (up to 12%) generated in large farm operations, without need for the removal of particulates. That need is eliminated through more effective retention of culture by means of an active three-phase separator. IBR is a case of a technology originally intended for a narrow application turning out to have much wider utility. Although mechanical work prior to anaerobic digestion is not eliminated, it is greatly reduced — because IBR “thrives on” particulate-laden influent. Also, processing is in a single stage with multiple tanks in parallel, which permits shut down of individual tanks without overall stoppage. IBR has the advantages of UASB without its intolerance of particulates, with all that that implies.

CSTR digestion. Continuous stirring (a.k.a., complete mixing) of anaerobically digesting liquor in sealed tanks is a transplant from aerobic sewage treatment practice. In aerobic treatment, vigorous mechanical agitation is employed to keep particulates in suspension and to introduce O_2 into solution. CSTR was transplanted to the anaerobic digestion of primary settled sewage and secondary waste activated sludge, for example, long before the profound difference between aerobic and anaerobic treatment was understood. It can now be seen that mechanical stirring discourages the formation of consortia and is inconsistent with the disparate growth rates and environmental requirement of acetogens and methanogens. The “give away” is that $SRT = HRT$, and that a lengthy HRT is necessary to achieve acceptable levels of treatment. Yet CSTR anaerobic digestion remains the standard in the U.S. municipal wastewater industry practice, and in professional organization guidance documents and wastewater engineering textbooks.

Leach bed digestion. This method is a transplant from aerobic composting. Fresh solid waste is heavily inoculated by mixing with previously processed material at high recycle ratios. Within a sealed vault, the new batch is irrigated with leachate amended with lime to counteract the decline in pH that would otherwise occur through acidogenesis getting ahead of methanogenesis. Gas is conveyed to storage. Material translocation into and out of the vault is via wheeled loader. A large component of a leach bed facility is after-the-fact aerobic composting, reflecting incomplete anaerobic digestion with much of the potential for methane production unexpressed.

Tall silo. This method involves very high recycle ratios. Successive batches are lifted to the top of a column to fill the void left by the gravitational descent and exiting of previous material. The moisture content of the mixture must be high enough so that it slips through the silo without getting hung up midway. Gas is collected from a capped space at the top. At tall silo facilities, finishing through aerobic composting is a major operation.

Decision-Making

The degradative part of the global carbon cycle taking place in anaerobic environments terminates in the generation of methane. It follows that even microbiologically uninformed anaerobic digestion methods spontaneously “work” in the limited sense of that word. But simply “working” does not suffice for today's demanding needs.

Decision-makers and their consultants attempting to evaluate alternative means of managing solid waste are familiar with mechanical aspects of processing, but not usually with microbial methanogenesis and its application in the form of anaerobic digestion. Since there are numerous ways to configure anaerobic digestion technologies, the evaluation of commercial offerings, to be meaningful, must enter the subject through the portal of microbiology.

Further Reading

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