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Contractor's Report

To The Board

Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste

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Executive Summary

Anaerobic digestion (AD) is a bacterial fermentation process that operates without free oxygen and results in a biogas containing mostly methane and carbon dioxide. It occurs naturally in anaerobic niches such as marshes, sediments, wetlands, and the digestive tracts of ruminants and certain species of insects. AD is also the principal decomposition process occurring in landfills.

AD systems are employed in many wastewater treatment facilities for sludge degradation and stabilization, and are used in engineered anaerobic digesters to treat high-strength industrial and food processing wastewaters prior to discharge. There are also many instances of AD applied at animal feeding operations and dairies to mitigate some of the impacts of manure and for energy production.

AD of municipal solid waste (MSW) is used in different regions worldwide to:

- Reduce the amount of material being landfilled
- Stabilize organic material before disposal in order to reduce future environmental impacts from air and water emissions
- Recover energy

Over the past 20 years, AD of MSW technology has advanced in Europe because of waste management policies enacted to reduce the long-term health and environmental impacts of landfill disposal. This has led to relatively high landfill tipping fees (compared with California or the U.S.), which, in combination with generous prices paid for renewable energy, has created an active commercial market for AD and other MSW treatment technologies in Europe. Installed AD capacity in Europe is more than 4 million tons per year.

In some parts of Europe, source separation of the organic fraction of municipal solid waste (OFMSW) is common and even mandatory, which contributes to the growth of biological treatment industries. Regions outside of Europe are also enacting more stringent waste disposal regulations, leading to the development of new AD and other MSW conversion plants.

Although the U.S. has a long history of treating agricultural and municipal wastewater with anaerobic digesters, no commercial-scale solid waste digesters are operating despite several favorable (though economically marginal) feasibility studies and laboratory findings.

Generally in the U.S. and most of California, landfills continue to be the lowest-cost option for managing MSW, since unlike Europe and Japan, space for new landfills is not as scarce, waste management policies are less rigorous, and full life-cycle costs and impacts are not accounted for. Furthermore, the energy market and regulatory mechanisms for licensing MSW AD and other conversion facilities in California have not been developed to easily accommodate commercial systems.

Composting of the OFMSW has increased significantly over the past 15 years, particularly for source-separated wastes, but by far the majority of the yard and food waste generated in the U.S. still goes to landfills. AD facilities are capable of producing energy and reducing the biodegradable content of the organic waste prior to composting, which reduces emissions of pollutants and greenhouse gases. However, these environmental and public health benefits have not been adequately internalized economically, especially considering the lack of familiarity with the technology. Investors and city planners will be more likely to adopt AD of MSW if additional revenues are provided initially. These revenues can come from supports for the energy produced (i.e. tax credits and guaranteed markets), increased tipping fees and, potentially, green or carbon credits.

Many European countries have passed laws mandating that utility companies purchase green energy, whereas in California few of the farms or wastewater treatment facilities that produce excess electricity from biogas have secured contracts with the utilities. Additionally, while European Union directives have called for mandatory pre-treatment and decreased disposal of biodegradable material in landfills, no equivalent regulations exist in federal or state codes. However, waste diversion requirements or targets exist in California and many other states in the U.S., and reducing OFMSW disposal has been a focus of waste managers and municipalities attempting to achieve the targets.

Nonetheless, interest in AD of MSW is growing, and several California jurisdictions are investigating landfill alternatives that include AD. The technologies have been used successfully for over ten years in Europe where the industry continues to expand. Facilities were also built recently in Canada, Japan, Australia and several other countries.

The European market has shown a large preference for single-stage over two-stage digesters and a slight preference for dry digestion systems over wet systems. However, the choice of AD technology depends on the composition of the waste stream, co-product markets, and other site-specific requirements. The design of any new digester facility should be based on a thorough feasibility study, and special attention should be paid to all aspects of the treatment process, including waste collection and transportation, pre-treatment processing (i.e. pulping, grinding, and sieving), material handling, post-treatment processing (i.e. aeration and wastewater treatment), public education, and strategic siting of the system.

Novel technologies are being developed, and several U.S. institutions hold patents on promising high-rate AD technologies. Many U.S. landfills are being built or modified to enhance biological degradation of the OFMSW and collect the resulting biogas, which may provide a stepping stone to full industrial "out-of-ground" AD of MSW. Landfill bioreactors may merit further consideration in their own right, but special attention should be paid to their performance and air/water emissions. In addition to electricity, other value-added product streams from AD systems could provide revenue to help improve the economic viability of organic waste treatment technologies. For example, technologies for upgrading biogas to natural-gas quality biomethane are available, as are technologies that utilize lignocellulosic materials which include residues from digesters. However, regulatory and definitional barriers need to be minimized in order to fully capitalize on these technologies and product streams.

The public desire for change in waste management practices will lead to a reduction in landfill availability. AD and other conversion technologies have the potential to minimize the environmental impact of waste disposal by reducing the amount of biodegradable materials in landfills. Public policies that encourage organic solid waste disposal reduction will help to facilitate the adoption of such technologies. In addition, as the technologies advance, their installation costs should decrease. However, as development of MSW AD facilities in the U.S.

proceeds, it would be wise to use the wealth of past experience available in order to reduce potential problems and expedite the development of organic waste treatment. AD technology developers need to work closely with waste collection and management companies in order to develop and implement appropriate digester system designs and material handling strategies and achieve successful enterprises.

Abbreviations and Acronyms

AB939	California State Assembly Bill 939
AD	anaerobic digestion/digester
ADC	alternative daily cover
BOD	biochemical oxygen demand
BOD-5	5-day biochemical oxygen demand
BTU	British thermal unit (a standard unit measure of energy)
C&D	construction and demolition waste
C/N	carbon to nitrogen ratio
CH_4	methane
CO_2	carbon dioxide
COD	chemical oxygen demand
CSTR	continuously stirred tank reactor
d	day
EC	European Community
EPR	extended producer responsibility
g	gram
GDP	gross domestic product
GHG	greenhouse gas
GWh	gigawatt hours (1 million megawatt hours)
H_2S	hydrogen sulfide
hr	hour
HRT	hydraulic retention time
ISO	international standards organization
kg	kilogram
kW	kilowatt
kWe	kilowatts of electricity
kWh	kilowatt hour
L	liter
lbs	pounds
LCA	life cycle assessment

m	meter
m^3	cubic meter (gas volumes assume 0°C and 1.101 bar)
mmBTU	million BTU
MBT	mechanical-biological treatment
MC	moisture content
MRF	material recovery facility
MS-OFMSW	mechanically sorted municipal solid waste
MSW	municipal solid waste
MT	metric ton
MW	megawatt
MWe	megawatts of electricity
MWh	megawatt hour
N:P:K	nitrogen to phosphorus to potassium ratio
NREL	National Renewable Energy Laboratory
OFMSW	organic fraction of municipal solid waste
OLR	organic loading rate
PIA	Prison Industry Authority
ppm	parts per million
PPP	purchasing power parity
rpm	revolutions per minute
scf	standard cubic feet (for gas volumes assume -32°F and 15.97 psi)
SMUD	Sacramento Municipal Utility District
SRT	solids retention time
SS-OFMSW	source separated municipal solid waste
tons	short ton
tpy	ton per year
TS	total solids
UMP	ultimate methane potential
UASB	upflow anaerobic sludge blanket
VS	volatile solids
WAS	waste activated sludge
y	year

Glossary of Terms

Alternative daily cover	Material other than soil used to cover the surface of active landfills at the end of each day to control diseases, fires, odors, etc.
Anaerobic digester	A dedicated unit process for controlling the anaerobic decomposition of organic material. Typically consists of one or more enclosed, temperature controlled tanks with material handling equipment designed to prevent the introduction of oxygen from the atmosphere.
Biomixer	A rotating drum often with a trommel screen used for size reduction and pretreatment of the organic fraction in mixed MSW for sorting. Can be aerated to encourage biological breakdown. Can be operated at retention times from several hours to several days.
Bioreactor-landfill	A landfill operated as a bioreactor using leachate recycling (or other management schemes) to increase the rate of organic decomposition and biogas production. Not to be confused with anaerobic digester.
Biochemical oxygen demand	Biochemical oxygen demand is the amount of oxygen required for complete (aerobic) biological decomposition of a material. The standard laboratory method (BOD_5) tests the amount of dissolved oxygen consumed in a closed aqueous system over a five-day period. It is a fairly direct but time-consuming measure of biodegradability of liquid streams.
Compost	Compost here refers to stabilized and screened organic material ready for horticultural or agricultural use. If anaerobically digested material is used as compost, it must be biologically stabilized, typically through aeration and maturation.
Continuously stirred tank reactor	A digester configuration in which the entire digester contents are mixed to create a homogeneous slurry.
Grey waste	The material left over after separation of recyclables and putrescible material from the mixed waste stream. Composed mostly of inorganic material, grey waste usually contains a significant amount of organic material. Depending on its composition, grey waste and can be treated biologically or burned prior to final disposal.
Hydraulic retention time	The average length of time liquids and soluble compounds remain in a reactor. Increasing the HRT allows more contact time between substrate and bacteria but requires slower feeding and/or larger reactor volume.
Mechanical-biological treatment	A waste processing system that combines a sorting facility for materials recovery (the mechanical portion) with biological treatment, either aerobic or anaerobic, for stabilizing the organic fraction before landfilling.
Materials recovery facility	A facility where mixed MSW is sorted in order to recover material for reuse or recycling. In California, the “post MRF fraction” is typically landfilled.
Mechanically separated OFMSW	Organic material separated from the mixed waste stream by mechanical means (i.e., trommels, screens, shredders, magnets,

	density dependent mechanisms). Isolating the OFMSW from mixed waste is less effective using mechanical separation as compared with source separation.
Municipal solid waste	MSW includes all of the solid wastes that are generated from residential (homes and apartments) sources, commercial and business establishments, institutional facilities, construction and demolition activities, municipal services, and treatment plant sites. Hazardous wastes are generally not considered MSW. Some regions or countries consider only residential solid waste as MSW
Organic fraction of municipal solid waste	The biogenic fraction of MSW. OFMSW can be removed from the waste stream at the source (source-separation), or downstream by mechanical separation, picking lines a combination of the two. The wood and paper fraction is more recalcitrant to biological degradation and is therefore not desired for biochemical conversion feedstocks
Plug flow digester	A digester in which materials enter at one end and push older materials toward the opposite end. Plug flow digesters do not usually have internal mixers, and the breakdown of organic matter naturally segregates itself along the length of the digester.
Pre-treatment	In reference to municipal solid waste, pre-treatment can refer to any process used to treat the raw MSW stream before disposal. This includes separation, drying, comminuting, hydrolysis, biological treatment, heating, pyrolysis, and others
Solids retention time	The average length of time solid material remains in a reactor. SRT and HRT are equal for complete mix and plug flow reactors. Some two-stage reactor concepts and UASB reactors decouple HRT from the SRT allowing the solids to have longer contact time with microbes while maintaining smaller reactor volume and higher throughput.
Source-separated OFMSW	Organic solid waste separated at the source (i.e., not mixed in with the other solid wastes). Often comes from municipal curbside recycling programs in which yard waste and sometimes kitchen scraps are collected separately from the rest of the MSW stream. The precise composition of SS-OFMSW can change significantly depending on the collection scheme used.
Total solids	The amount of solid material (or dry matter) remaining after removing moisture from a sample. Usually expressed as a percentage of the as-received or wet weight. Moisture content plus TS (both expressed as percentage of wet weight) equals 100 percent.
Ultimate methane potential	This is a standard laboratory technique used to measure the anaerobic biodegradability and associated methane yield from a given substrate. The test is run until no further gas production is detected and can last up to 100 days. The results can be influenced by the substrate concentration and particle size, the inoculum source, the food to microorganism ratio, and the presence or build-up of inhibitory compounds among others. (Also known as ultimate biomethane potential, BMP, and B_o.)

Volatile solids	The amount of combustible material in a sample (the remainder is ash). The value is usually reported as a percentage of the TS, but may occasionally be given as a fraction of the wet weight. VS is used as an indicator or proxy for the biodegradability of a material, though recalcitrant biomass (i.e., lignin) which is part of the VS is less digestible. Because of the simplicity of the measurement procedure, it is commonly reported in the AD literature.

Background on Anaerobic Digestion of Municipal Solid Waste

Anaerobic digestion (AD) is a biological process typically employed in many wastewater treatment facilities for sludge degradation and stabilization, and it is the principal biological process occurring in landfills. Many livestock farms in the U.S. are turning to the use of AD as a means of mitigating the environmental impacts of manure lagoons with some capture of methane for energy production. Internationally, AD has been used for decades, primarily in rural areas, for the production of biogas for use as a cooking and lighting fuel. Many household-scale digesters are employed in rural China and India for waste treatment and gas production. More recently, Europe has developed large-scale centralized systems for municipal solid waste treatment with electricity generation as a co-product. Other industrialized countries have followed the European model.

Biodegradation of organic material occurs in nature principally through the action of aerobic microorganisms. Ultimately, complete oxidation of the carbonaceous organic materials results in the production of carbon dioxide (CO_2) and water (H_2O). Anaerobic microorganisms degrade the organic matter in the absence of oxygen with ultimate products being CO_2 and methane (CH_4), although lignin and lignin-encased biomass degrade very slowly. Anaerobic microorganisms occur naturally in low-oxygen niches such as marshes, sediments, wetlands, and in the digestive tract of ruminant animals and certain species of insects.

Digestion Process Description

The anaerobic digestion of organic material is accomplished by a consortium of microorganisms working synergistically. Digestion occurs in a four-step process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (see Figure 1):

1. Large protein macromolecules, fats and carbohydrate polymers (such as cellulose and starch) are broken down through hydrolysis to amino acids, long-chain fatty acids, and sugars.
2. These products are then fermented during acidogenesis to form three, four, and five-carbon volatile fatty acids, such as lactic, butyric, propionic, and valeric acid.
3. In acetogenesis, bacteria consume these fermentation products and generate acetic acid, carbon dioxide, and hydrogen.
4. Finally, methanogenic organisms consume the acetate, hydrogen, and some of the carbon dioxide to produce methane. Three biochemical pathways are used by methanogens to produce methane gas. The pathways along with the stoichiometries of the overall chemical reactions are:
    a. Acetotrophic methanogenesis: $4\ CH_3COOH \rightarrow 4\ CO_2 + 4\ CH_4$
    b. Hydrogenotrophic methanogenesis: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$
    c. Methylotrophic methanogenesis: $4\ CH_3OH + 6\ H_2 \rightarrow 3\ CH_4 + 2\ H_2O$

Methanol is shown as the substrate for the methylotrophic pathway, although other methylated substrates can be converted. Sugars and sugar-containing polymers such as starch and cellulose yield one mole of acetate per mole of sugar degraded. Since acetotrophic methanogenesis is the primary pathway used, theoretical yield calculations are often made using this pathway alone.

From the stoichiometry above, it can be seen that the biogas produced would theoretically contain 50 percent methane and 50 percent carbon dioxide. However, acetogenesis typically produces some hydrogen, and for every four moles of hydrogen consumed by hydrogenotrophic methanogens a mole of carbon dioxide is converted to methane. Substrates other than sugar, such as fats and proteins, can yield larger amounts of hydrogen leading to higher typical methane content for these substrates. Furthermore, hydrogen and acetate can be biochemical substrates for a number of other products as well. Therefore, the overall biogas yield and methane content will vary for different substrates, biological consortia and digester conditions. Typically, the methane content of biogas ranges from 40-70 percent (by volume).

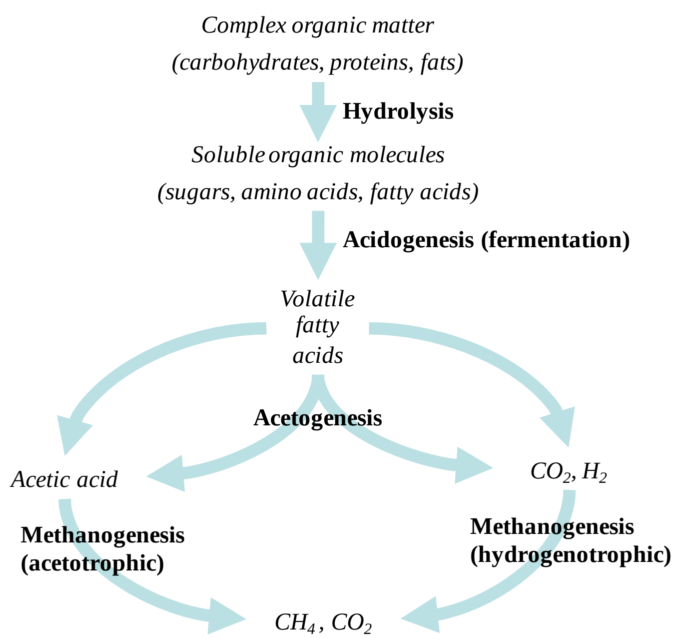


Figure 1. Anaerobic digestion biochemical conversion pathways

Anaerobic conditions are required for healthy methanogenesis to occur. This means that the reactors used must be well sealed which allows the biogas to be collected for energy conversion and eliminates methane emissions during the anaerobic digestion process. In addition to methane and carbon dioxide, semi-harmful contaminants such as hydrogen sulfide and ammonia are produced, albeit in much smaller amounts (<1 percent by volume). The production of these trace gases in the biogas depends on the sulfur and nitrogen contents of the feedstock. However, these elements are also nutrients required by the bacteria, so they cannot be eliminated completely.

In fact, anaerobic digestion requires attention to the nutritional needs of the bacteria degrading the waste substrates. The most important nutrients for bacteria are carbon and nitrogen, but these two elements must be provided in the proper ratio. Otherwise, ammonia can build up to levels that can inhibit the microorganisms. The appropriate carbon/nitrogen (C/N) ratio depends on the digestibility of the carbon and nitrogen sources; therefore, the appropriate C/N ratio for organic MSW may be different from that for other feedstocks such as manure or wastewater sludge.

In general, the optimal conditions for anaerobic digestion of organic matter are near-neutral pH, constant temperature (thermophilic or mesophilic), and a relatively consistent feeding rate.

Imbalances among the different microorganisms can develop if conditions are not maintained near optimum. The most common result of imbalance is the buildup of organic acids which suppresses the methanogenic organisms adding to even more buildup of acidity. Acid buildup is usually controlled naturally by inherent chemical buffers and by the methanogens themselves as they consume acids to produce methane. These natural controls can break down if too much feed is added and organic acids are produced faster than they are consumed, if inhibitory compounds accumulate, or if the feed stream lacks natural pH buffers such as carbonate and ammonium.

Solid concentrations higher than about 40 percent TS can also result in process inhibition, likely due to the reduced contact area available to the AD microorganisms. The TS content of OFMSW typically ranges from 30-60 percent, thus some water may need to be added. Process water can be used, but this may also result in the buildup of inhibitory compounds. Thus, low-solids digesters require the addition of fresh water. Higher temperatures result in faster reaction kinetics which, in practice, translates to smaller reactors needed to process a given waste stream. However, the micro-organisms themselves are adapted to relatively narrow temperature ranges. Mesophilic and thermophilic microbes are adapted to roughly 30-40 °C (86-104 °F) and 50-60 °C (122-140 °F) respectively.

State of MSW Disposal in the U.S. and Europe

U.S. and California

Californians produce over 2.2 MT (2.5 tons) [1] of municipal solid waste (MSW) per person per year. This has grown from 1.4 MT (1.5 tons) per capita since 1993 [1, 2]. Roughly 40-60 percent of MSW generated is organic[2] [2-4]. Despite large gains in waste reduction and diversion in California since the enactment of California State Assembly Bill 939 (AB 939) in 1989, California was still landfilling 38 million MT (42 million tons) of MSW in 2006 or 1 MT (1.1 tons) per capita, and using 3 million MT (3.3 million tons) of green waste as alternative daily cover (ADC) [1, 5].[3]

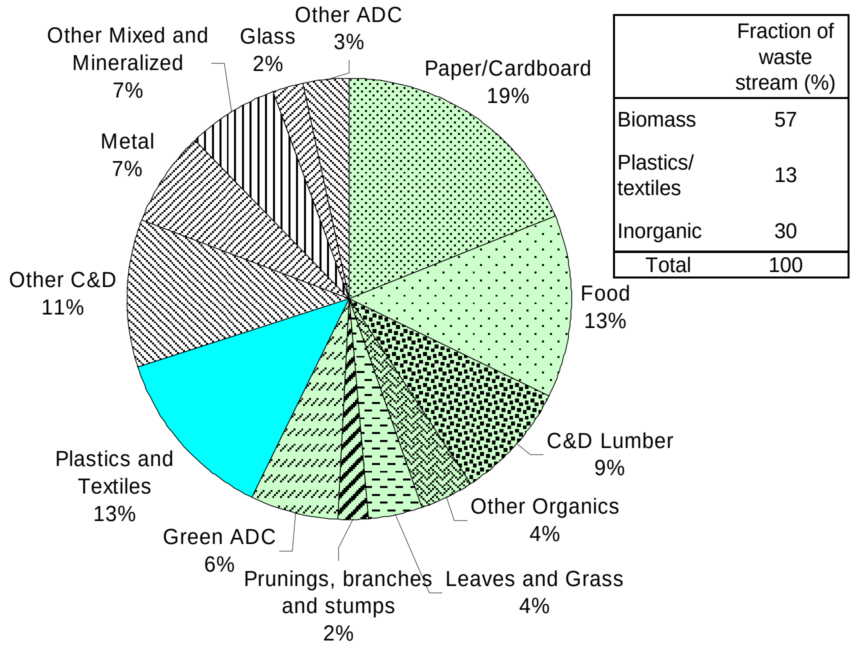
Of the combined MSW and green ADC landfilled in 2006, some 24.2 million MT (26.7 million tons) were of biological origin (biogenic), 5.4 million MT (5.9 million tons) were plastics and textiles, and the remaining 12.8 million MT (14.1 million tons) were minerals and other inorganic materials (glass, metal, non-wood construction/demolition waste and inorganic ADC) (see Figure 2) [6].

---

[1] Metric (or Système International [SI]) units are used in this report in following the standard for scientific papers. The equivalent U.S. Customary units will be listed in parentheses immediately following the metric value. For weights, 1 metric ton (MT) [or 1,000 kg] is typically equated to 1.102 short tons (tons), where a short ton is equal to 2,000 pounds in U.S. Customary units. For electrical power measurements watts will be used without conversion.

[2] Technically, “organic” includes the vast majority of compounds that contain carbon, which includes plastics and textiles. However, in this report, “organic” refers to biomass or “biogenic material” in the waste stream which does not include plastics and textiles, but does include paper, yard, and food wastes.

[3] In “State of Garbage in America” (April 2006) BioCycle Magazine estimated the average U.S. per capita disposal at 1.0 MT (1.1 ton) per year and the average U.S. diversion or recycle rate at 36 percent. The CIWMB now estimates that diversion for California is 54 percent even though per capita disposal in California is about the same as the U.S. average. This implies inconsistencies between U.S. and the California gross waste generation estimates.



	Fraction of waste stream (%)
Biomass	57
Plastics/ textiles	13
Inorganic	30
Total	100

Figure 2. California landfilled waste stream by material type [7]

The energy potential represented by organic waste landfilled in California is more than15,000 GWh/y of electricity [2]. This is equivalent to the annual output of a 1,700 MW power plant or 8 percent of the total electricity consumption of the state [2]. For energy production from MSW, dry materials (such as paper, wood, and plastic) are most suited to thermal conversion technologies which can quickly convert almost the entire organic fraction to energy. Several of the state's 31 biomass power facilities have access to urban wood fuel diverted from landfill and there are three dedicated MSW mass burn facilities in the state. About 1.5 million MT (1.7 million tons) of urban wood wastes and 1.0 million MT (1.1 million tons) of mixed wastes are burned for power [8]. However, the relatively large moisture content (MC) of non-woody MSW makes the material difficult to burn and reduces the conversion efficiency. Therefore the OFMSW is often better suited to biochemical conversion (i.e. AD or landfill bioreactors). Food and green wastes landfilled in California represent about 2,300 GWh/y of electricity if converted via AD ([2]).

Much of the organic fraction can also be composted for soil amendment and nutrient recovery. Composting of OFMSW has become an important alternative to landfilling in California and the U.S. In the U.S., composting increased from 2 percent of the disposed MSW in 1990 to 8 percent in 2005 (see Figure 3) [9]. As of 1999 there were nine operating composting plants in the U.S. processing OFMSW along with other organic materials (such as yard and wood waste). At that time the only plant in California was a proposed 100 MT/d (110 tons/d) facility in Mariposa County [10, 11]. By 2005, there were at least three operating facilities in California that accepted OFMSW: the Mariposa facility, with a final capacity of 60 MT/d (66 tons/d); Jepson Prairie near Dixon, which processed 240 MT/d (264 tons/d); and Z-Best Composting in Gilroy [12]. A CIWMB survey identified 101 operational composting facilities in California in 2003, 80 percent of which were accepting green wastes but only 10 percent of which were accepting food wastes [13]. No data were available on the amount of different waste types being composted. Combined, these facilities treated 4.3 million MT (4.7 million tons) of waste from all sources.

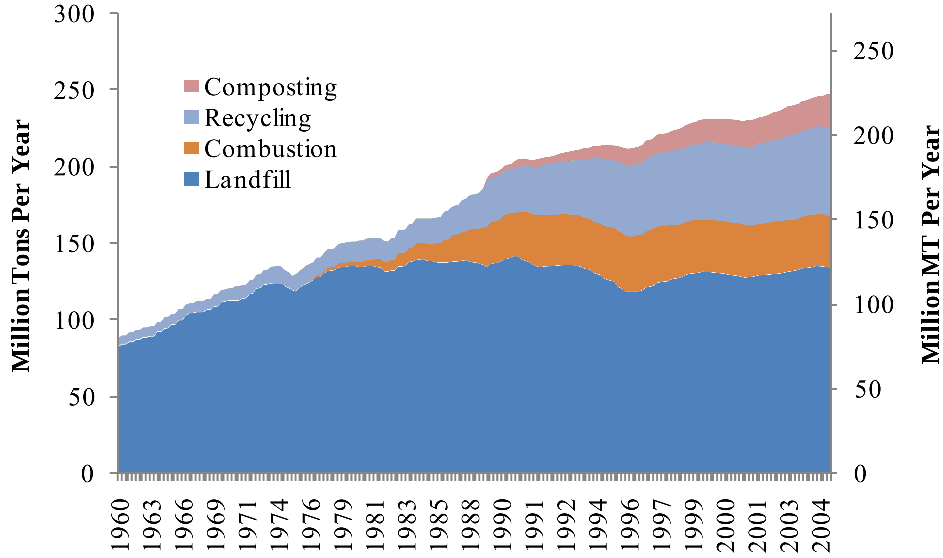


Figure 3. Trend in disposal and recovery of MSW in the U.S.
(does not include construction and demolition debris, non-hazardous industrial waste, or wastewater treatment sludge). Adapted from U.S. Environmental Protection Agency data [9].

AB 939, which established the California Integrated Waste Management Board (CIWMB), mandated that waste jurisdictions divert 25 percent of their waste streams from landfills by 1995, increasing to 50 percent by 2000 [14][4]. AB 939 represented landmark legislation for California and many politicians and waste management experts believe it solved the waste disposal crisis that was facing California [15]. Although no recycling/reduction regulations specific to the organic fraction of MSW exist in the state code, recycling and diversion of the organic fraction has been a focus of many attempts to meet waste diversion goals [15, 16].

Despite advances in organic waste diversion, no commercial MSW AD facilities have been built in California (although several California jurisdictions or waste handlers have or are considering large scale MSW AD). Ten digesters have been built at California dairies since 2001 as part of the California Energy Commission's Dairy Power Production Program. An additional nine were funded in 2006 [17], and at least five California food processors have AD facilities for treating wastewater [18].

Handling and treatment of OFMSW is more difficult than treating wastewater or manure. As such, the AD of OFMSW requires a larger amount of investment and technological experience. Furthermore, capital and operating costs are higher for AD than for composting or landfilling. The low tipping fees charged by landfills in the U.S. and relatively low energy prices compared to those in Europe make it difficult for AD and other conversion technologies to be cost-competitive [16, 19]. However, life-cycle analyses (LCA) have shown that AD of MSW reduces the environmental impact and is more cost-effective (in Europe) on a whole-system basis than landfilling or composting over the life of the project (see Life Cycle Analysis) [20-23].

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[4] For more information on the history of California's waste diversion efforts see the CIWMB web site http://www.ciwmb.ca.gov/Statutes/Legislation/CalHist/1985to1989.htm.

Europe

The European Community (EC) passed a regulation in 2002 to standardize reporting and timing of data collection for waste disposal, and the first year of data was included in the most recent Eurostat Yearbook (2006-2007) [24]. For comparison with past years, only average per capita statistics were reported (see Figure 4). As of 2004, Europeans disposed of an average of 0.6 MT (0.7 tons) of MSW [24]; however, unlike U.S. statistics on MSW production, this waste did not include construction and demolition debris which makes up 30 percent of the reported MSW in the U.S. [9]. Nonetheless, the Western European average per capita disposal was almost half of the U.S. average and less than half of the California average [25].

In Europe, the per capita MSW production increased over the past ten years, but landfill disposal declined slightly. Per capita combustion with energy recovery has remained relatively constant while composting, recycling, and other treatments almost doubled since 1995 [24]. OFMSW typically comprises 50-60 percent by weight of the solid waste stream collected by municipalities in Europe that do not practice source separation. In 2004, this totaled some 200 million MT (220 million tons) [26, 27].

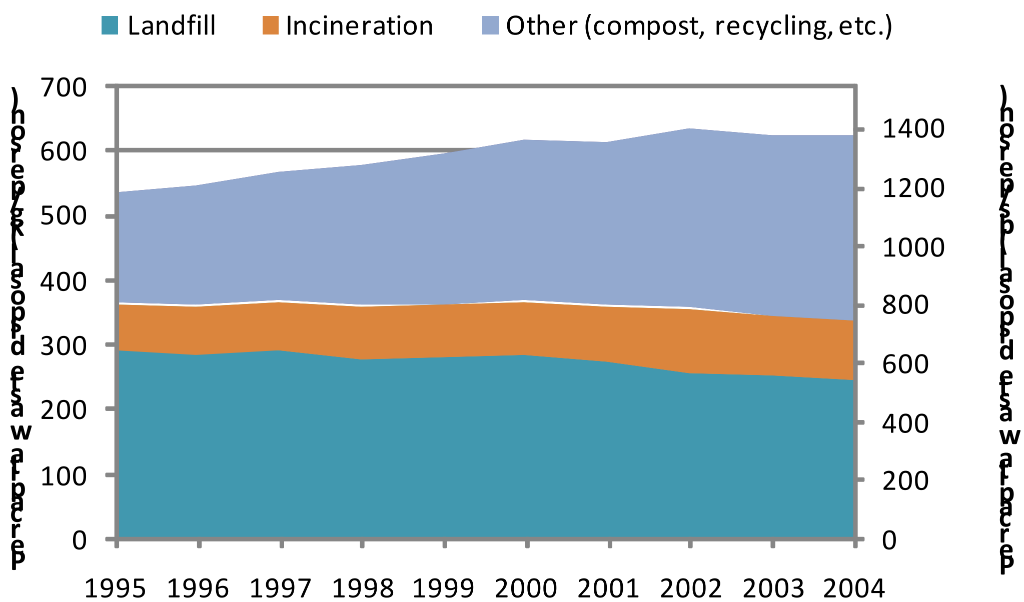

Figure 4. European trend in annual per capita MSW disposal by method [24].

In 1999, the EC adopted the Landfill Directive (Council Directive 99/31/EC) which became enforceable in 2001. It required the biodegradable portion of MSW to be reduced by 25 percent of that disposed in 1995 within five years, 50 percent within eight years, and 65 percent within 15 years [28].

Furthermore, Article 6(a) required that all waste that gets landfilled must be treated, with the exception of inert materials “for which treatment is not technically feasible.” Each country in the EC is held to this standard as a minimum requirement, but in practice Germany, Austria, Denmark, Luxembourg, the Netherlands, and Belgium had already imposed such restrictions and now have even stricter requirements while France, Italy, Sweden, England and Finland converted their facilities subsequent to adopting the law [27]. Greece, Ireland, Portugal and Spain were in the process of converting their facilities as of 2004 [27].

As a consequence, installed AD capacity in Europe has increased sharply and now stands at more than 4 million tons annual capacity (Figure 5). Most notably, Spain recently installed several large-scale AD facilities and now processes over 1 million tons OFMSW per year which accounts for over 50 percent of the organic waste produced there [29].

In Germany the Recycling and Waste Law, the Directive on Residential Waste Disposal, the Federal Ordinance on Handling of Biowaste, and the Ordinance for Environmentally Sound Landfilling set stringent limits for the composition of treated MSW prior to disposal in landfills [30-32]. For example, in Germany the upper limits on total organic carbon and energy content of material going to landfill were set at 18 percent and 6,000 kJ/kg (2,580 BTU/lb) [33].

Furthermore, energy prices in Europe are generally higher than in the U.S. and many European countries provide financial incentives to renewable energy producers. For example, in Germany the Renewable Energy Act guaranteed renewable electricity producers a high percentage of the retail electricity price (75-90 percent) with biomass earning 0.15-0.25 $/kWh (converted from Euros to PPP-adjusted U.S. dollars) [34]. Tariffs with prescribed annual reductions were guaranteed for up to 20 years. The regulation also required utilities to connect renewable producers to the grid. In addition many AD of MSW facilities in the EU also sell green certificates and carbon credits. Direct subsidies and soft loans are also used to support new renewable energy producers.

Categories of Engineered AD Systems

Vandevivere et al. [35] categorized the most common MSW AD technologies as follows:

- One-stage Continuous Systems
  - Low-solids or ‘Wet’
  - High-solids or ‘Dry’
- Two-stage Continuous Systems
  - Dry-Wet
  - Wet-Wet
- Batch Systems
  - One Stage
  - Two Stage

Single-stage digesters are simple to design, build, and operate and are generally less expensive. The organic loading rate (OLR) of single-stage digesters is limited by the ability of methanogenic organisms to tolerate the sudden decline in pH that results from rapid acid production during hydrolysis. Two-stage digesters separate the initial hydrolysis and acid-producing fermentation from methanogenesis, which allows for higher loading rates but requires additional reactors and handling systems. In Europe, about 90 percent of the installed AD capacity is from single-stage systems and about 10 percent is from two-stage systems (see Figure 5).

Another important design parameter is the total solids (TS) concentration in the reactor, expressed as a fraction of the wet mass of the prepared feedstock. The remainder of the wet mass is water by definition. The classification scheme for solids content is usually described as being either high-solids or low-solids. High-solids systems are also called dry systems and low-solids systems may be referred to as wet systems. A prepared feedstock stream with less than 15 percent TS is considered wet and feedstocks with TS greater than 15-20 percent are considered dry (although there is no established standard for the cutoff point). Feedstock is typically diluted with process water to achieve the desirable solids content during the preparation stages.

Before AD became an accepted technology for treating MSW, single-stage wet digesters were used for treating agricultural and municipal wastewater. However, MSW slurry behaves differently than wastewater sludge. Because of the heterogeneous nature of MSW, the slurry tends to separate and form a scum layer which prevents the bacteria from degrading these organics [35]. The scum layer tends to evade the pump outlets and can clog pumps and pipes when it is removed from the reactors. To prevent this, pretreatment to remove inert solids and homogenize the waste is required. Solids can also short circuit to the effluent pipe before they have broken down completely, therefore design modifications were made to allow longer contact time between bacteria and dense, recalcitrant material [35].

Furthermore, MSW tends to contain a higher percentage of toxic and inhibitory compounds than wastewater. In diluted slurry, these compounds diffuse quickly and evenly throughout the reactor. In high enough concentrations, this can shock the microorganisms, whereas in a dry system the lower diffusion rate protects the microbes [35].

Because of these constraints, dry systems have become prevalent in Europe (see Figure 5), making up 60 percent of the single-stage digester capacity installed to date [29]. Dry digesters treat waste streams with 20-40 percent total solids without adding dilution water [35]. However, these systems may retain some process water or add some water either as liquid or in the form of steam used to heat the incoming feedstock. Furthermore, as organic matter breaks down, the internal MC of the digester will increase. Based on personal communication with the plant manager of one industrial dry digester (Peter Magielse, Brecht, Belgium, July 12, 2007) the MC increases from 64 percent to 72 percent. Nonetheless, heavy duty pumps, conveyors, and augers are required for handling the waste, which adds to the systems' capital costs. Some of this additional cost is offset by the reduction in pretreatment equipment required. Most dry digesters operate as plug flow digesters, but due to the viscosity of the feed, the incoming waste does not mix with the contents of the digester [35]. This prevents inoculation of the incoming waste which can lead to local overloading. Therefore, most of the digester designs include an inoculation loop in which the incoming OFMSW is mixed with some of the exiting digestate paste prior to loading.

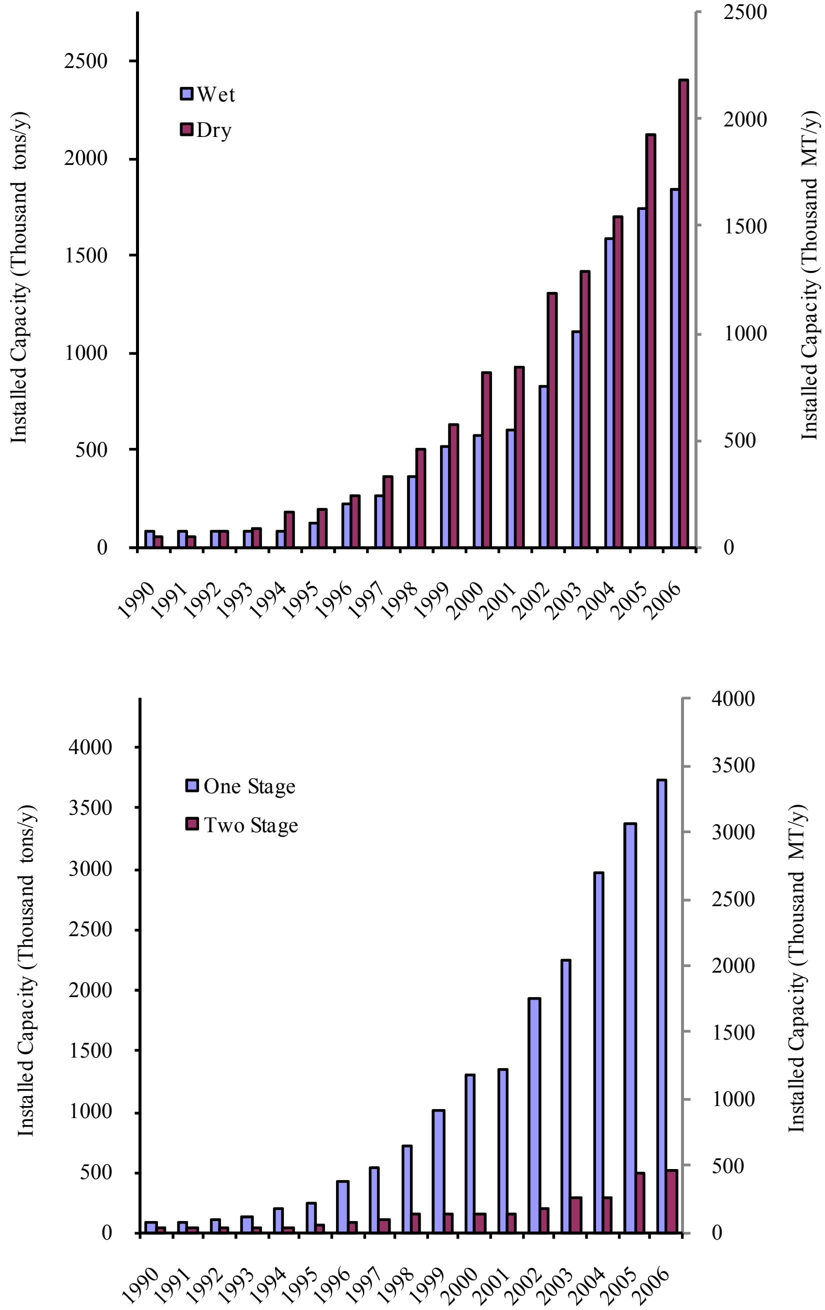

Figure 5. Growth of MSW anaerobic digester technology by solids content (<5% TS = wet, >20% TS = dry) and number of stages.
Adapted from De Baere [29]

Multi-stage systems are designed to take advantage of the fact that different portions of the overall biochemical process have different optimal conditions. By optimizing each stage separately, the overall rate can be increased [36]. Typically, two-stage processes attempt to optimize the hydrolysis and fermentative acidification reactions in the first stage where the rate is limited by hydrolysis of complex carbohydrates. The second stage is optimized for methanogenesis where the rate in this stage is limited by microbial growth kinetics. Since methanogenic archaea prefer pH in the range of 7–8.5 while acidogenic bacteria prefer lower pH, the organic acids are diluted into the second stage at a controlled rate. Often a closed recirculation loop is provided to allow greater contact time for the unhydrolyzed organic matter.

Some multi-stage systems apply a microaerophilic process in an attempt to increase the oxidation of lignin and make more cellulose available for hydrolysis [37, 38]. Although adding oxygen to an anaerobic environment seems counterintuitive, sludge granules can shield the obligate anaerobes from oxygen poisoning and the practice has been shown to increase biogas yield in some situations [37-40]. In two-stage systems, because methanogens are more sensitive to oxygen exposure than fermentative bacteria, the air may preferentially inhibit methanogens, which could help maintain a low pH in the hydrolysis stage. However, if the oxygen is not completely consumed and the biogas contains a mixture of oxygen and hydrogen and/or methane, hazardous conditions could be created.

Process flexibility is one of the advantages of multi-stage systems. However, this flexibility also increases cost and complexity by requiring additional reactors, material handling and process control systems. On the opposite end of the spectrum, batch or sequential batch systems aim to reduce complexity and material handling requirements. As opposed to continuous wet and dry systems, the feedstock does not need to be carefully metered into a batch reactor, thereby eliminating the need for complex material handling equipment. The primary disadvantage of batch digesters is uneven gas production and lack of stability in the microbial population. To surmount these issues, batch systems can also be combined with multi-stage configurations.

Material Handling Systems

European technologies all use extensive pre- and post-digestion processing units, regardless of the waste source or digester type. Pre-sorting is necessary to prevent clogging of the pumps and to reduce the amount of reactor volume occupied by inert material. Even source-separated waste inevitably contains metal and plastic contaminants and must be pre-sorted. A typical sorting line includes the following components;

- Receiving
  - Can include some visual (manual or robotic) sorting and removal of bulky or potentially harmful items
  - Provides a buffer for inflow rate fluctuations
- Particle size reduction
  - Can be mechanical and/or biological
  - Relies on the relative ease of reducing the particle size of the organic fraction
- Separation
  - Can be based on magnetism, density, and size

Figure 6 shows some of the material processing units used in the Dranco and Valorga dry digester systems. The receiving area allows for unloading of raw MSW and isolation of MSW from different sources. Some receiving areas use robotics to minimize human contact with the waste. Others incorporate a sorting line for workers to manually remove the most obvious inorganic materials. Once the MSW has been loaded into the mechanical separation system, human contact is minimal as biological and mechanical processes prepare the MSW for density and/or size separation.

Density separation requires wetting the MSW; therefore it is more commonly applied when using low-solids digesters. Organic material breaks into smaller particles more easily than inorganic material, therefore a mechanical macerator or agitator is often employed prior to screening. In addition, some aerobic treatment can help break down the organic matter. This may also be accompanied by a loss of digestible organic matter; therefore short retention times are used. Between several hours and one or two days is typical for rotating drums, or “biomixers,” which combine agitation with aerobic treatment. Biomixers are currently used at about 20 MSW plants in the U.S. for aerobic composting where retention times of 3-5 days are used.

Recently the researchers at the University of California, Davis studied the biogas production potential from the organic materials separated from MSW using rotating drums at six MSW composting facilities in the U.S. They found that the organic materials had high biogas and methane yields even when the MSW had spent only 24 hours in the drum (unpublished data). This indicates that AD systems could be incorporated into the existing MSW composting operations in the U.S. for energy recovery from OFMSW. In a rotating drum system, a sieve may line the sides of the drum allowing undersized particles to pass to the dosing unit while expelling oversized, primarily inorganic, particles. Alternatively, the waste may pass through one or more trommel screens after the drum for sieving. Dosing units store mixed waste to even out fluctuations in the content and volume of MSW going to the digester. They can also be used for heating and inoculating the digester feed. Heat may be added as steam, which can be produced using waste heat from engine generators. Some systems have a separate feed mixer which combines the sorted MSW with digester paste in order to inoculate the new feed and bring it to the appropriate MC.

Figure 6. Dry digester material handling equipment.
Clockwise from top left: staging area with robotic claw; rotating biomixer drum; overs from trommel screen sieves; high-speed drum with integrated sieve and magnetic separator; high-solids slurry pump; feed mixer with steam injection; and dosing unit with steam injection and high-solids slurry pump.

In Bassano, Italy a Valorga digester accepts source-separated waste and grey waste [41]. As can be seen from the diagram below, even source-separated waste passes through a primary sieve and a magnetic metals removal unit. The grey waste which is the inorganic fraction of the source-separated waste consists primarily of inorganic materials. (In fact, organics make up only 10-16 percent of this material, and paper makes up an additional 34-50 percent.) The grey waste passes through an additional drum screen and densimetric separator which suspends the waste in water, removing the floating layer as well as the heavy particles that sink to the bottom [41].

SS-OFMSW --> bags broken --> mechanical separation (first pass) --> magnetic separation --> size reduction to 10mm --> digester

Grey MSW --> bags broken --> mechanical separation (first pass) --> magnetic separation --> size reduction --> drum screen --> densimetric separation --> digester

Figure 7. Bassano, Italy pre-processing diagram.
Adapted from Bolzonella [41].

The Treviso wastewater treatment facility found its anaerobic digesters to be too large for processing waste activated sludge (WAS) only, so they built a separation unit to remove the organic fraction of MSW for co-digestion with the sludge [42]. As can be seen in Figure 8, the waste passes through a shredder and magnetic separator, then a second shredder and trommels, and finally a density separator. The emerging waste is 96 percent organics and paper as compared with 76 percent for the incoming waste, and 24% of the incoming organic and paper materials are lost during the sorting process. Metals are reduced by 100 percent, plastics are reduced by 93 percent, and glass is reduced by 98 percent.

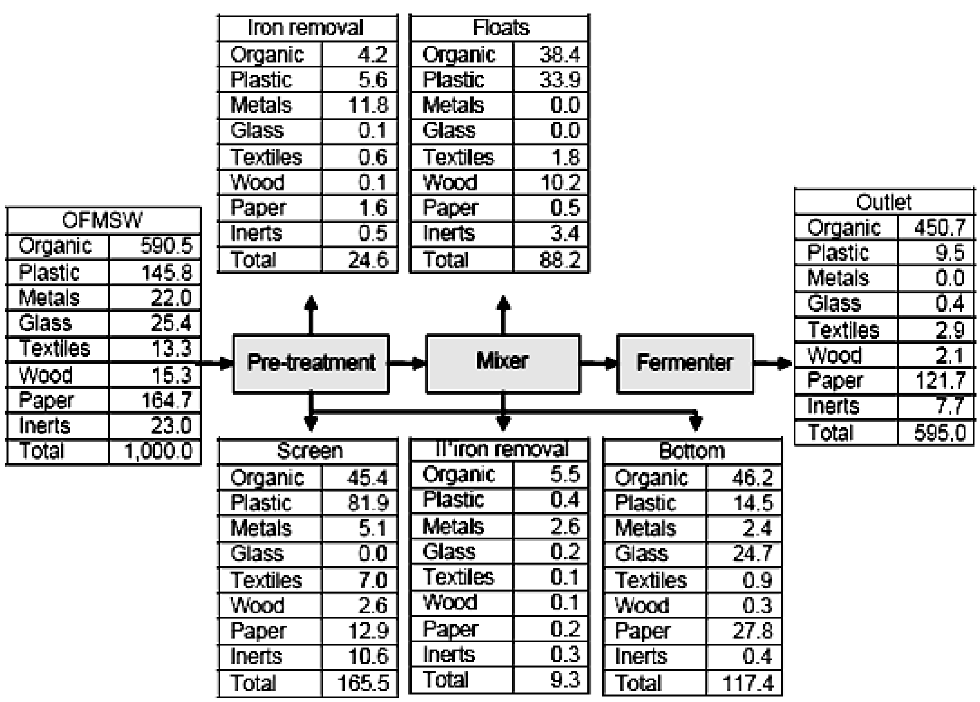

Figure 8. Mass balance of the Treviso wastewater treatment digester sorting line

(Modified to accept MSW as well as WAS [42])

The digestate that exits an anaerobic digester contains undigested organics that will continue to break down if not treated further (see Figure 9) [2, 20, 30]. This can lead to methane emissions typically not accounted for when analyzing the environmental impact of AD. In the EU and particularly in Germany, where the composition of OFMSW entering a landfill is tightly regulated, extensive post-treatment processing is incorporated into the AD facility. This eliminates transportation costs which could be quite high considering the relatively high MC (40-50 percent) of the exiting digestate.

It should be noted, however, that the inorganic materials separated from the incoming MSW stream still have to be transported to a processing facility, typically a material recovery facility or landfill. Dewatering units allow for the re-capture of process water which can provide inoculant and reduce the cost of adding water to the digester. A novel digester in Canada subjects digester paste to a steam treatment step followed by a second digester in order to produce a high quality peat for use as a planting medium [43].

Figure 9. Aerobic composting treatment for the post-digestion material.
From left to right: digester press cake from screw press, aerobic aeration bins for digester press cake, and a digester facility with enclosed aeration beds in foreground and maturation beds in background.

Review of Commercial AD Technologies for MSW Treatment

A number of commercial vendors have designed a variety of digesters for the global market (see Table 1). These commercial systems span the full range of categories of engineered AD systems. The following review attempts to summarize the research reported in the literature for many of the existing and emerging systems, with special attention paid to the most commercially successful and innovative systems.

Table 1. Summary of commercial anaerobic digester technologies with large scale reference plants

Data from the company websites as of February 2008 and adapted from Nichols [44].

Process System Name	No. of Plants[1]	Capacity Range (tons/y)[2]	No. of Stages		Total Solids Content		Operating Temperatures	
			1	2	< 20%	> 20%	35°C (95°F)	55°C (130°F)
AAT	8	3,000 to 55,000	x		x		x	
ArrowBio	4	90,000 to 180,000		x	x		x	
BTA	23[4]	1,000 to 150,000	x	x	x		x	x
Biocel	1	35,000	x			x	x	
Biopercolat	1	100,000		x		x	x	
Biostab	13	10,000 to 90,000	x		x			x
DBA-Wabio	4	6,000 to 60,000	x		x		x	
DRANCO	17	3,000 to 120,000	x			x		x
Entec	2	40,000 to 150,000	x		x		x	
Haase	4	50,000 to 200,000		x	x		x	x
Kompogas	38	1,000 to 110,000	x			x		x
Linde-KCA/BRV	8	15,000 to 150,000	x	x	x	x	x	x
Preseco	2	24,000 to 30,000						
Schwarting-Uhde	3	25,000 to 87,600		x	x			x
Valorga	22	10,000 to 270,000	x			x	x	x
Waasa	10+	3,000 to 230,000	x		x		x	x

[1] Includes operational or planned plants that accept any of the following: MSW, kitchen waste, food waste, yard waste, or green waste. Does not include food processing waste or wastewater. May include co-digestion with other organics such as biowaste or sewage sludge. Pilots and demonstrations were excluded.

[2] Because metric tons are only slightly larger than short tons and the capacity range is approximate, no conversion was included.

[3] Plants installed utilizing the firm's services and/or components.

NOTE: The above list is not exhaustive and system names may change as companies acquire and develop new technologies.

Single-stage Wet Systems

Single-stage wet systems have been built by a number of different companies throughout Europe. Since this was the most familiar configuration from wastewater treatment, it was one of the first systems tested on OFMSW. Below, the Waasa system is described in detail, but other companies have also provided components and full scale systems to many wet OFMSW digesters, most notably Biotechnische Abfallverwertung GmbH & Co. KG (BTA) and Linde-KCA (see Table 1).

Waasa

The Waasa system, built in 1989 and named after the city in Finland in which it was developed, was one of the original MSW digesters. Today there are at least ten operational Waasa plants in Europe (see Table 1)[5].

The Waasa system consists of a vertical pulper that homogenizes the incoming MSW and removes floating debris from the surface and sunken grit from the bottom of the pulper. Density-fractionated MSW is then pumped to the pre-chamber of a continuously stirred tank reactor (see Figure 10). The pre-chamber helps alleviate short circuiting and an inoculation loop ensures that incoming waste is exposed to microorganisms in order to minimize acid buildup.

The largest Waasa plant is located in Groningen, Netherlands, where four 2,740 m^3 (725,000 gal) tanks treat 92,000 MT/y (101,000 tons/y) of OFMSW out of an initial 250,000 MT/y (275,000 tons/y) of raw MSW [44]. This system produces 0.10-0.15 m^3/kg (3.2-4.8 scf/lb) biogas from wet source-separated waste, with a weight reduction of 50-60 percent [44]. This is a relatively high biogas yield, indicating high digestibility of the feedstock and good conversion efficiency in the digester.

Although Nichols did not report TS or VS data, the typical OLR for a single-stage wet system is 4-8 kg VS/m^3/d (0.033-0.066 lbs VS/gal/d) [45]. Assuming 15 percent of the reactor volume is gas head space, the working volume would be 9,350m^3 (2,470,000 gal), thus the wet loading rate would be 27 kg/d (59 lbs/d) and the resulting VS content would be 20-40 percent. Assuming 30 percent VS content and a biogas yield per wet ton of 125 m^3 (4,410 scf), the average specific biogas yield would be 0.417 m^3/kg VS (13.4 scf/lb).

[5] The original construction company, Citec, Finland, no longer appears to operate the digesters, as indicated by removal of all AD information from the Citec website.

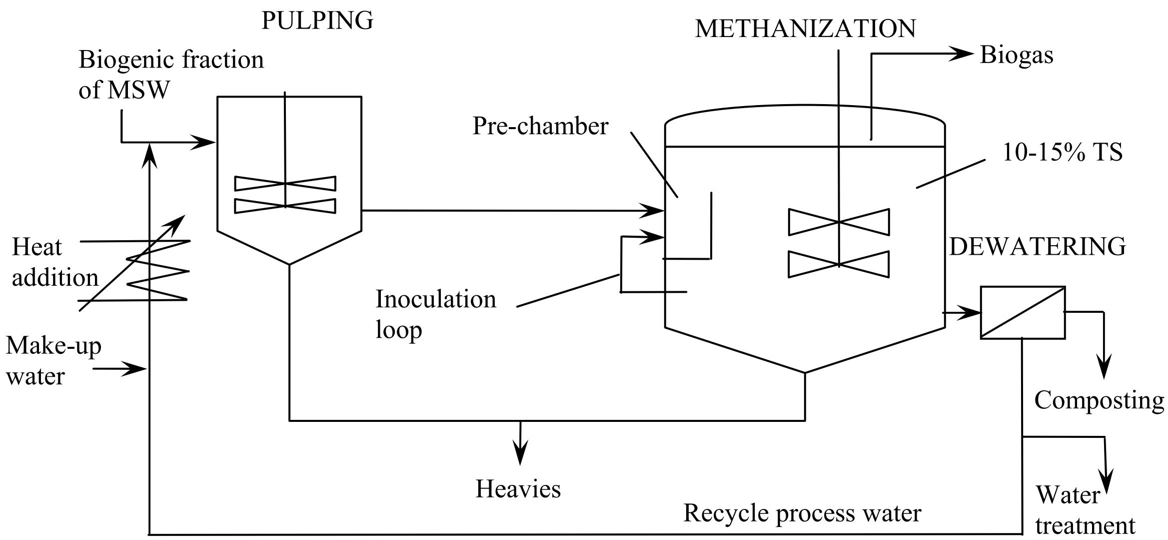

Figure 10. Schematics of the Waasa one-stage digestion process [45].

BIMA

Entec Biogas GmbH of Austria builds digesters that treat primarily agricultural, industrial, and municipal wastewater. One system designed for Schaalsee Biogas & Recycling GmbH in Kogel, Germany treats food and restaurant waste from Hamburg and Mecklenburg Vorpommern in two 2,600 m^3 (690,000 gal) constantly stirred tank reactors. The operation of the system mirrors that of the Waasa digester.

The company also designed a self-mixing system known as the BIMA digester which eliminates mechanical mixing by utilizing the pressure differential between two chambers within the reactor (see Figure 11). The company reported that a 150,000 MT/y (165,000 tons/y) version of the system was being built in Lucknow, India, but as of the time of publication the system had not begun operating[6]. Details on the operational parameters and performance of the digester and the status of the Lucknow project were not available.

[6] The authors found no publications specific to this system. All data were from http://www.entec-biogas.at, accessed on Feb. 13, 2008.

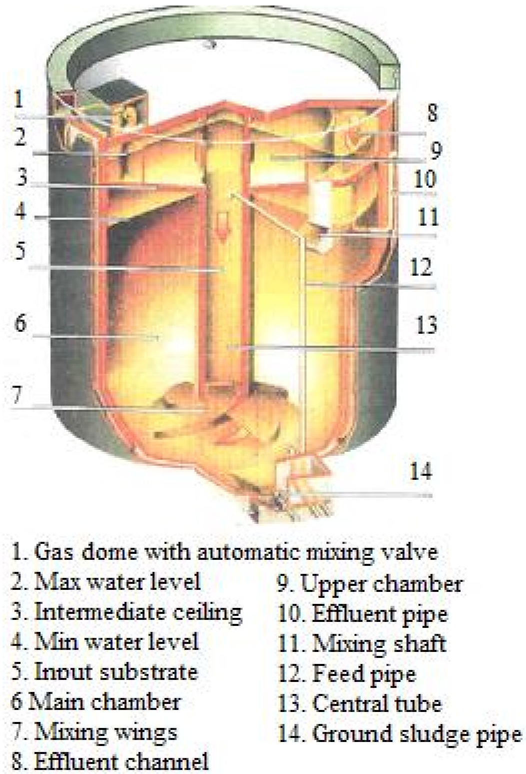

Figure 11. The BIMA digester designed by Entec Biogas GmbH
(adapted from a presentation by V. V. N. Kishore for the Department for Environment, Food, and Rural Affairs, New Delhi, India, November 2006).

Single-stage Dry Systems

In dry, or high-solids, systems, the digester contents are kept at a solids content of 20-40 percent TS (equivalent to 60-80 percent MC). Handling material at high solids concentration requires different pre-treatment and transfer equipment (i.e., conveyor belts, screws, and special pumps for the highly viscous streams). Research in the 1980s indicated that biogas yields and production rates for single-stage dry systems were as high as or greater than that of wet systems [46]. The challenge of dry systems is handling, mixing, and pumping the high-solids streams rather than maintaining the biochemical reactions.

Although some of the handling equipment (such as pumps capable of handling high-solids slurries) may be more expensive than those for wet systems, the dry systems are more robust and flexible regarding acceptance of rocks, glass, metals, plastics, and wood pieces in the reactor. These materials are not biodegradable and will not contribute to biogas production but they generally can pass through the reactor without affecting conversion of the biomass components. The only pretreatment required is removal of the larger pieces (greater than 5 cm [2 in]), and minimal dilution with water to keep the solids content in the desired range. This allows for reduced sorting equipment costs which can offset some of the additional material handling expenses.

Because of their high viscosity, loading rate, and rapid hydrolysis, materials in dry reactors move via plug flow (materials added on one end of the digester push older materials toward the opposite end), and the incoming feedstock needs to be inoculated or mixed to avoid localized acid

buildup. Two of the most commonly used commercial-scale designs inoculate the feedstock by mixing it with a portion of the digested material, while another incorporates mixing via high-pressure biogas injection
(see

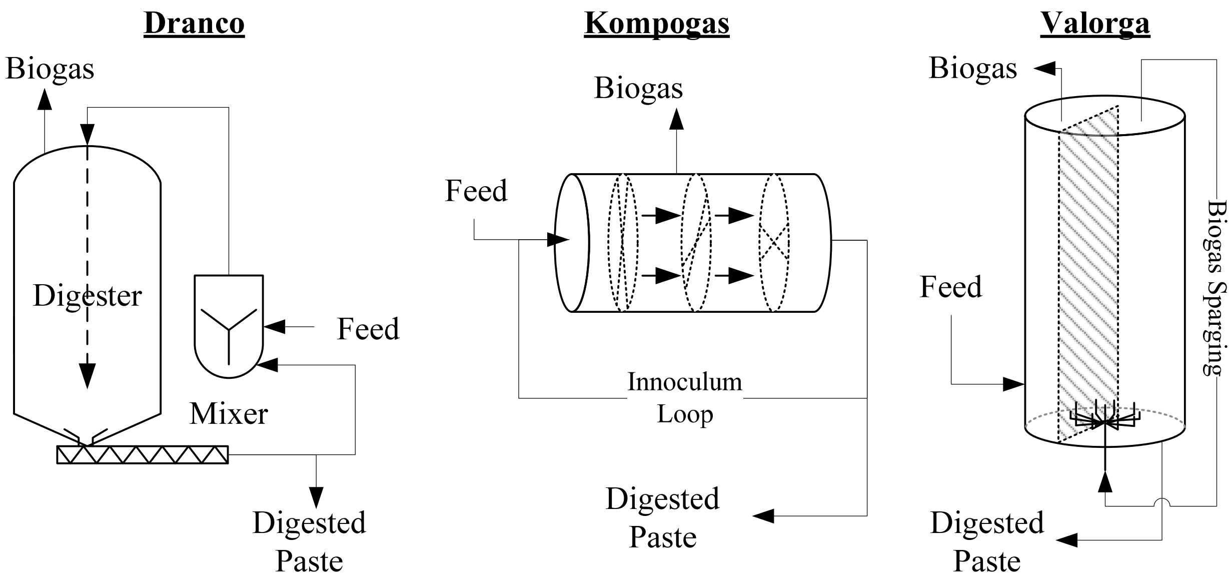

Figure 12). All three systems operate as plug-flow digesters.

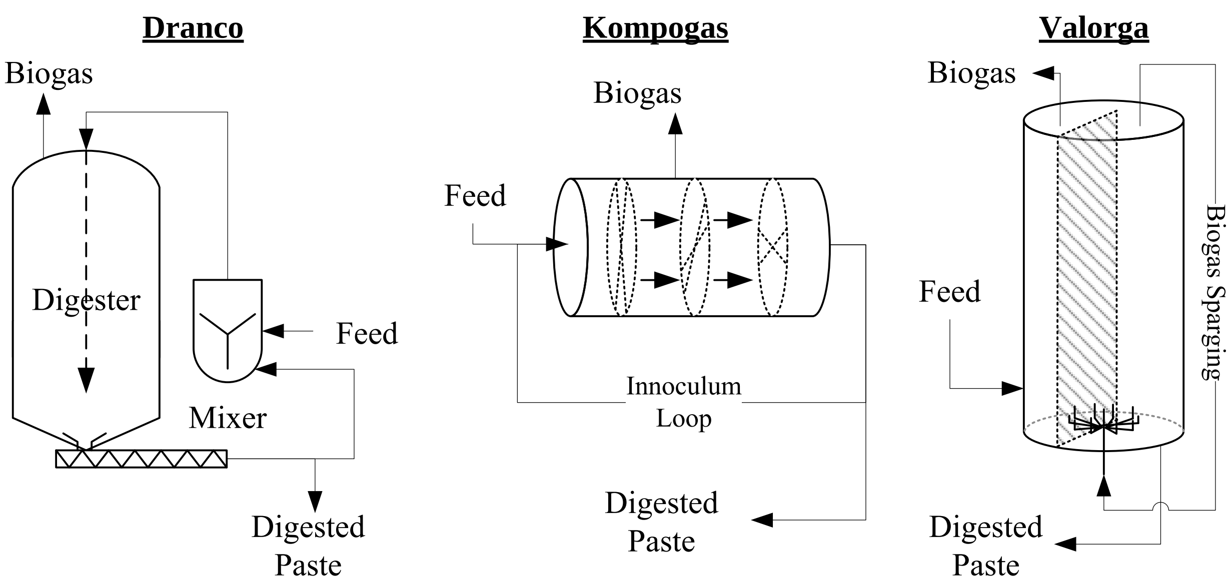

Figure 12. High-solids single-stage digester designs

Adapted from Vandevivere [35].

Organic Waste Systems (Dranco Process)

Organic Waste Systems (OWS) was established in 1988 and maintains labs in Belgium and Ohio (the company has no known projects in the U.S.). OWS also has an exclusive partner in Japan for proposed facilities there. The company designs, builds, and operates AD plants for MSW as well as integrated solid waste management systems and consults on biodegradation and waste management. OWS markets the Dranco (Dry Anaerobic Composting) process as well as the Soridsep (Sorting–Digestion-Separation) integrated waste treatment system. The technology is patented under international patent number WO 02102966.

The Dranco process was developed in the late 1980s. It is a high-solids, single-stage anaerobic digestion system that operates at thermophilic temperatures [47]. Feed is introduced into the top of the reactor and moves downward to the conical bottom where an auger removes digestate. A fraction of the digestate is transferred to the mixing pump where it is blended with fresh feed to inoculate the material and steam to bring the feed to the working temperature. The rest of the digestate is dewatered to produce process water and press cake. There is no mixing within the reactor, other than that brought about by the downward, plug-flow movement of the waste and some biogenic gas that bubbles upwards. The press cake contains active bacteria, some ammonia, and undigested solids and must be aerobically stabilized for use as agricultural compost. Source separated household and industrial wastes are preferred in order to maintain the quality of the compost.

Existing commercial Dranco systems (see Table 2) are reported to have biogas yields in the range of 0.103 – 0.147 m^3/kg (1.65 – 2.35 scf/lb) wet weight [48]. The Dranco process produces a compost product and heat or electricity from the biogas. The company reports that electricity production can range from 0.17 to 0.35 MWh/MT (0.15 – 0.32 MWh/ton) feedstock[7].

Table 2. Dranco dry-digester reference plants.
From Organic Waste Systems Inc. website accessed February 2008.

Dranco Process Locations		Capacity (thousand MT/y)	(thousand tons/y)	Substrate	Year Operation Began
Tenneville	Belgium	39	42.9	Biowaste	Planned for 2008
Alicante	Spain	30	33	Mixed waste	Planned for 2008
Hotaka	Japan	3	3.3	Biowaste	Planned for 2007
Vitoria	Spain	120	132	Mixed waste	2006
Terrassa	Spain	25	27.5	Biowaste	2006
Münster	Germany	24	26.4	Residual waste	2005
Hille	Germany	38	41.8	Residual waste	2005
Pusan	Korea	70	77	Biowaste	2005
Leonberg	Germany	30	33	Biowaste	2004
Rome	Italy	40	44	Biowaste	2003
Brecht II	Belgium	50	55	Biowaste	2000
Villeneuve	Switzerland	10	11	Biowaste	1999
Kaiserslautern	Germany	20	22	Residual waste	1999
Aarberg	Switzerland	11	12.1	Biowaste	1998
Bassum	Germany	13.5	14.9	Residual waste	1997

[7] For more information see the OWS company website: http://www.ows.be/dranco.htm.

Dranco Process Locations		Capacity (thousand MT/y)	(thousand tons/y)	Substrate	Year Operation Began
Bergheim-Siggerwiesen	Austria	20	22	Biowaste	1993
Brecht I	Belgium	20	22	Biowaste	1992
Total	18 plants	564	620		
Average		33	36		

The Dranco system has garnered interest in the academic literature due to the performance of the system. A high average loading rate of 15 kg VS/m^3/d (0.13 lbs/gal/d) was maintained in the Dranco digester in Brecht, Belgium over a one year period. The conditions inside the reactor were 35 percent TS and 14 day hydraulic retention time (HRT) [35]. The performance of the Brecht plant was reported as 65 percent VS destruction with a 0.103 m^3/kg (1.65 scf/lb) wet weight biogas yield. The TS content in the feedstock was reported at 40 percent and the VS content (as a percentage of TS) was 55 percent [48]. By inference, the specific biogas yield for the system was 0.468 m^3/kg VS (7.50 scf/lb VS). This relatively low yield along with the relatively low VS destruction may indicate that a large portion of the VS loaded was recalcitrant which explains how such a high loading rate was achieved. To support this theory, it was reported that the waste composition was 15 percent kitchen waste, 75 percent garden waste, and 10 percent paper, whereas a Dranco system in Salzburg, Austria treating 80 percent kitchen waste and 20 percent garden waste achieved a biogas yield of 0.622 m^3/kg VS (9.96 scf/lb) [48]. The VS destruction and OLR were not reported, but elsewhere it has been stated that the typical Dranco system is designed for 12 kg VS/m^3/d (0.1 lbs/gal/d) [35].

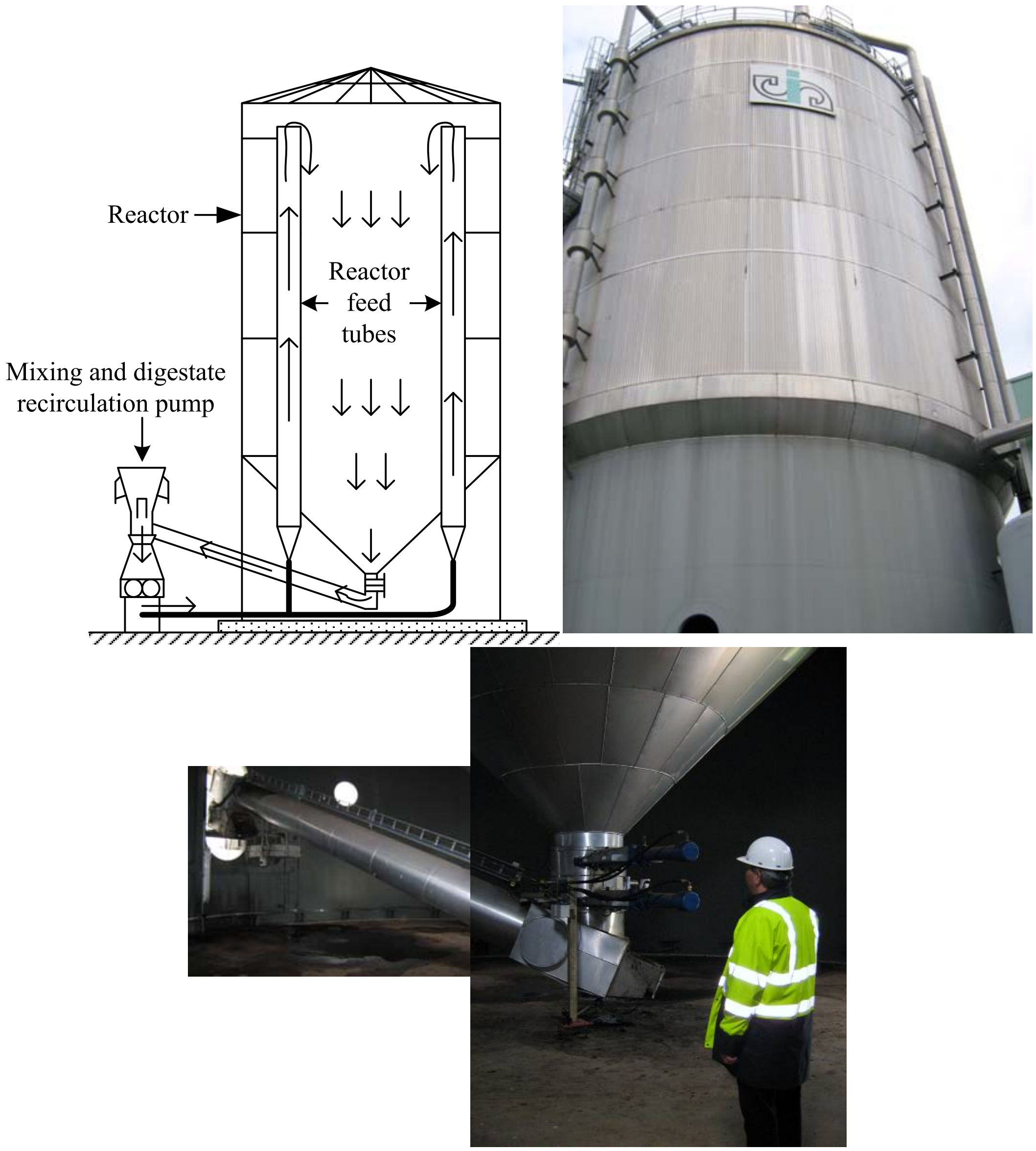

Figure 13. Dranco reactor
Sketch and flow diagram (top left). Dranco reactor (top right) and conical botom with digestate augur (bottom). Note: gas collection tubes are omitted from the sketch for clarity.

The author of this report visited the Brecht Dranco digester in July 2007. The site consists of two single-stage vertical digesters both operated at 50°C (122°F). The first digester (Dranco I) was built at the beginning of the 1990s with a designed capacity of 7,500 MT/y (8250 tons/y). As one of the first Dranco systems, improvements made in the subsequent 15 years allowed the digester operators to increase the loading rate to its current level of 20,000 MT/y (22,000 tons/y).

In 2000 a second digester was added to the Brecht site (Dranco II). The new digester is 3,100 m^3 (830,000 gal) and accommodates 50,000 wet MT/yr (55,000 tons/y) or 137 MT/d (150 tons/d) assuming a 100 percent capacity factor. In fact, according to the Brecht plant manager, operation is only halted for regular maintenance eight days per year.

Feeding occurs continuously for 16 hrs/d during the week and 12 hrs/d on the weekends. This staggered feeding schedule helps provide an indication of the health of the microorganisms based on how quickly they respond to the changing amount of feed. Incoming source-separated OFMSW (SS-OFMSW) is mixed with digestate in the ratio of 1:6 (OFMSW:digestate) thereby recycling some of the microorganisms as well as some of the water. As digestate and fresh feedstock are mixed, steam is added to heat the feed to 50°C (122°F). The optimal temperature range for thermophilic methanogens is 55-60°C (131-140°F). However, the plant manager contended that keeping the temperature slightly lower than optimal reduced inhibition due to ammonia production. This would also reduce the energy required to heat the feed. The total liquid volume of water added as steam is on the order of 2–4 m^3/d (500 – 1,000 gal/d). Mixing is accomplished by recycling digestate during feeding, which requires cement pumps capable of handling the thick slurry.


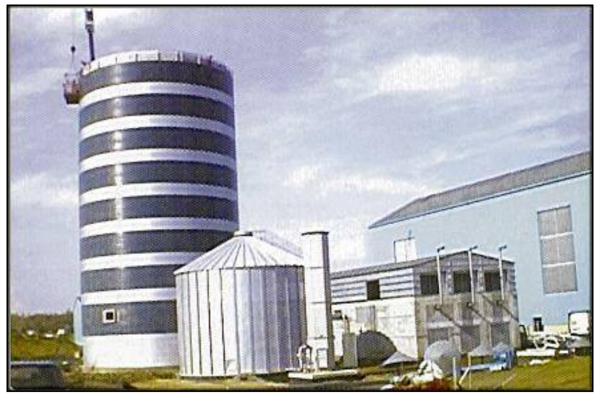

Figure 14. Valorga digesters
SIVOM plant in Varennes-Jarcy, France (left); Mons, Belgium (right).

Waste Recovery Systems, Inc. (Steinmüller Valorga process[8])

The Valorga process was developed in 1981 to treat organic solid waste and accepts MSW after appropriate separation of the recalcitrant fraction [44]. A high-solids digester is fed with OFMSW that has 25-30 percent TS content adjusted using steam for heating and process water for diluting the incoming feed as needed [44]. Mesophilic or thermophilic systems are used depending on feedstock and economics.

The reactor is a continuous single-stage modified plug-flow reactor. Typical plug-flow reactors involve only natural mixing, but the Valorga digester uses pressurized biogas for mixing. This eliminates the need for an inoculation loop. The reactor consists of a vertical outer cylinder with an inner wall extending to about ⅔ of the diameter of the tank
(see

[8] For more information, see the Valorga International website: http://www.valorgainternational.fr/en/.

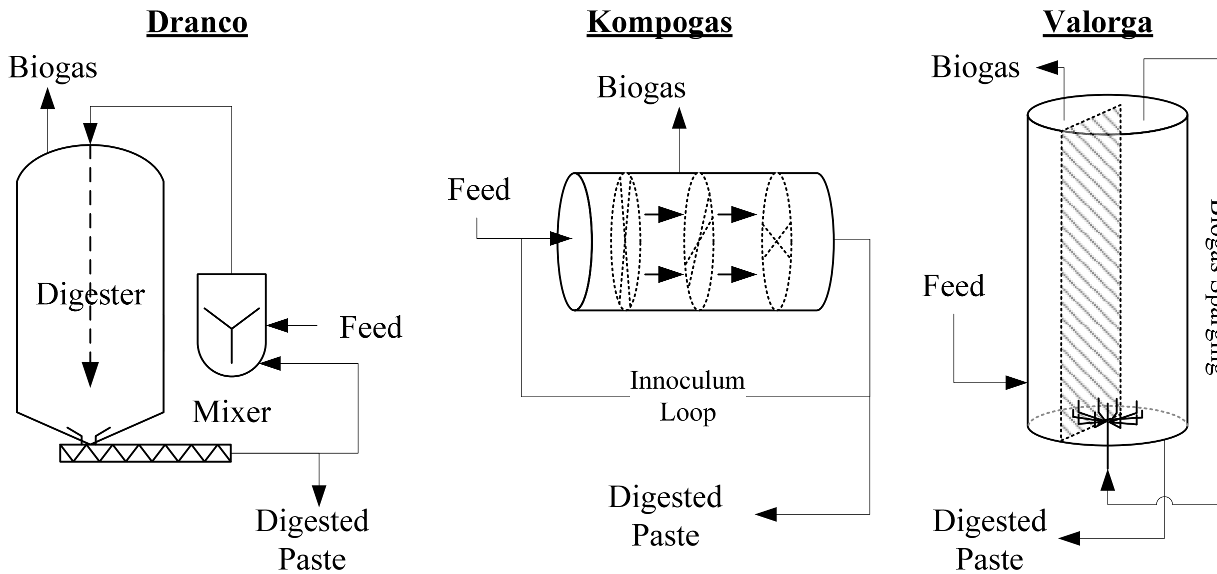

Figure 12). Material enters at the bottom on one side of the inner wall and must flow around the wall before it can exit [49]. The retention time is on the order of three weeks. Biogas is injected in the base of the reactor and the bubbles serve as a means for mixing and keeping solids suspended. The digestate is dewatered and typically composted. Table 3 lists existing Valorga facilities.

With 21 operating facilities as of 2008 (assuming the plants under construction in 2007 are currently operational see Table 3), the Valorga system is a robust and popular one-stage dry system. According to Nichols (2003), feedstocks with less than 20 percent TS do not perform well in the Valorga system because dense grit particles settle out too quickly and clog the gas recirculation vents. Biogas yields have been reported in the range of 0.22–0.27 m^3/kg VS (7.05–8.65 scf/lb VS) which corresponds to 0.80–0.16 m^3/wet kg (2.6–5.1 scf/wet lb), indicating a VS content in the OFMSW of 35-60 percent [44]. The solid retention time is 18-23 days and post digestion solids composting takes about two weeks [44]. Valorga plants are currently operating in Spain, Germany, Italy, Switzerland, and the Netherlands [50].

The author of this report visited the Varennes-Jarcy Valorga facility in July 2007. The plant treats a total of 100 MT/y (110 tons/y) of MSW: 70 MT/y (77 tons/y) mechanically sorted OFMSW (MS-OFMSW) and 30 MT/y (33 tons/y) source sorted OFMSW (SS-OFMSW). A remotely operated mechanical claw loads the waste into a 50 m (160 ft) rotating drum with a 2-3 day retention time. Although the drum is not aerated, the temperature of the MSW increases indicating the possibility of biological activity to help break down the organic fraction into smaller particles which are screened out. These “fines” are sent to a dosing unit for storage and steam heating prior to being pumped into one of the three 4,000 m^3 (1 million gal) reactors.

Under typical operating conditions the SS-OFMSW and MS-OFMSW are loaded into separate tanks and the digestate is treated separately, allowing plant operators to control the quality of the compost produced. Dewatering occurs in three steps resulting in process water containing less than 3 percent TS (according to the plant manager). The solids are transferred to an enclosed aeration bed where air heated by waste generator heat is blown through the curing piles and sucked through vents in the roof to a scrubber and biofilter. Large automated mechanisms turn the compost and transfer it to a maturation bed after 2-3 weeks (see Figure 6, center).

Table 3. Reference Valorga digester installations
(As of February 2008)

Location		Capacity (thousand tons/y)	Capacity (thousand MT/y)	Start-up Date
Fos sur Mer	France	88	97	2008*
Zaragoza	Spain	95	105	2007*
Las Dehesas	Spain	195	215	2007*
Beauregard Barret	France	30	33	2007*
Saint Barthelemy de Vais	France	40	44	2007*
Etoile sur Rhone	France	80	88	2007*
Shanghai	China	268	295	2007*
Beijing	China	105	115	2007*
Tondela	Portugal	35	39	2007*
Calais	France	28	31	2007*
Barcelona (Ecopark II)	Spain	120	132	2004
Bassano	Italy	55	61	2003
Hanover	Germany	125	138	2002
Cadiz	Spain	115	127	2002
Varennes-Jarcy	France	100	110	2002
Mons	Belgium	59	65	2002
La Coruna	Spain	142	156	2001
Geneva	Switzerland	10	11	2000
Freiburg	Germany	36	40	1999
Engelskirchen	Germany	35	39	1998
Tilburg	Netherlands	52	57	1994
Amiens	France	85	94	1988
Total	22 plants	1898	2088	
Average		86	95	

* New plants planned, but operation had not begun as of February 2008.

Kompogas AG (Kompogas process)

Unlike the other two popular single-stage dry digesters above, the Kompogas system utilizes a horizontal plug flow digester with internal rotors to assist in degassing and homogenizing the waste [44, 45]. The system is prefabricated in two sizes: 15,000 or 25,000 MT/y (16,500 or 27,600 tons/y). Larger capacities can be acquired by combining the units in parallel. The internal MC has to be carefully maintained at 72–77 percent in order for the system to flow properly; therefore some of the process water and/or digestate is mixed with incoming OFMSW [45]. This also ensures that incoming feed is inoculated in order to prevent excessive acid buildup near the front end of the digester.

Table 4. Reference Kompogas facilities
Data from the company website as of February 2008.

Location	Country	Capacity (thousand MT/y)	Capacity (thousand tons/y)	Installation Year
Sierre	Switzerland	70	77	2009
Florsheim-Wicker	Germany	45	50	2008
Rostock	Germany	40	44	2008
Montpellier	France	100	110	2008
Botarell	Spain	54	59	2008
Ilbenstadt	Germany	18.5	20	2007
Regen	Germany	18	20	2007
Amtzell	Germany	18.5	20	2007
Utzenstorf	Switzerland	12	13	2007
Langenthal	Switzerland	4	4	2006
Ottenbach	Switzerland	16	18	2006
Aarberg	Switzerland	12	13	2006
Pratteln	Switzerland	15.5	17	2006
Martinique	Caribbean	20	22	2005
Rioja	Spain	75	83	2005
Lenzburg	Switzerland	5	6	2005
Passau	Germany	39	43	2004
Kyoto	Japan	20	22	2004
Weissenfells	Germany	12.5	14	2003
Bachenbülach	Switzerland	12.5	14	2003
Oetwil am See	Switzerland	10	11	2001
Roppen	Austria	10	11	2001
Volketswil	Switzerland	5	6	2000
Jona/Rapperswil	Switzerland	5	6	2000
Frankfurt	Germany	15	17	1999
Alzey-Worms	Germany	24	26	1999
Kyoto	Japan	1	1	1999
Niederuzwil	Switzerland	13	14	1998
Hunsrück	Germany	10	11	1997
Lustenau	Austria	10	11	1997
München-Erding	Germany	24	26	1997
Braunschweig	Germany	2	2	1997

Location	Country	Capacity (thousand MT/y)	(thousand tons/y)	Installation Year
Otelfingen	Switzerland	12	13	1996
Kempten	Germany	10	11	1996
Samstagern	Switzerland	10	11	1995
Bachenbülach	Switzerland	10	11	1994
Rümlang	Switzerland	8.5	9	1992
Rümlang	Switzerland	0.5	1	1989
Total	38 plants	788	867	
Average		21	23	

The system operates with a retention time of 15-20 days under thermophilic conditions. Biogas yield was reported at 0.11–0.13 m^3/kg (3.4–4.2 scf/tons) wet weight[9]. Solids content and reduction data were not found in the literature. Currently at least 30 systems are operating in Europe [44]. The corporate website claims 50 digesters operating throughout the world via licensing agreements with 6 partners in Europe, 2 in the U.S., 1 in Africa, 2 in Russia, 11 in Asia, and 1 in Australia[10]. Thirty-eight systems are listed on the Kompogas home page (see Table 4).

[9] From the Kompogas website: http://www.kompogas.ch/en/index.html.

[10] Ibid.

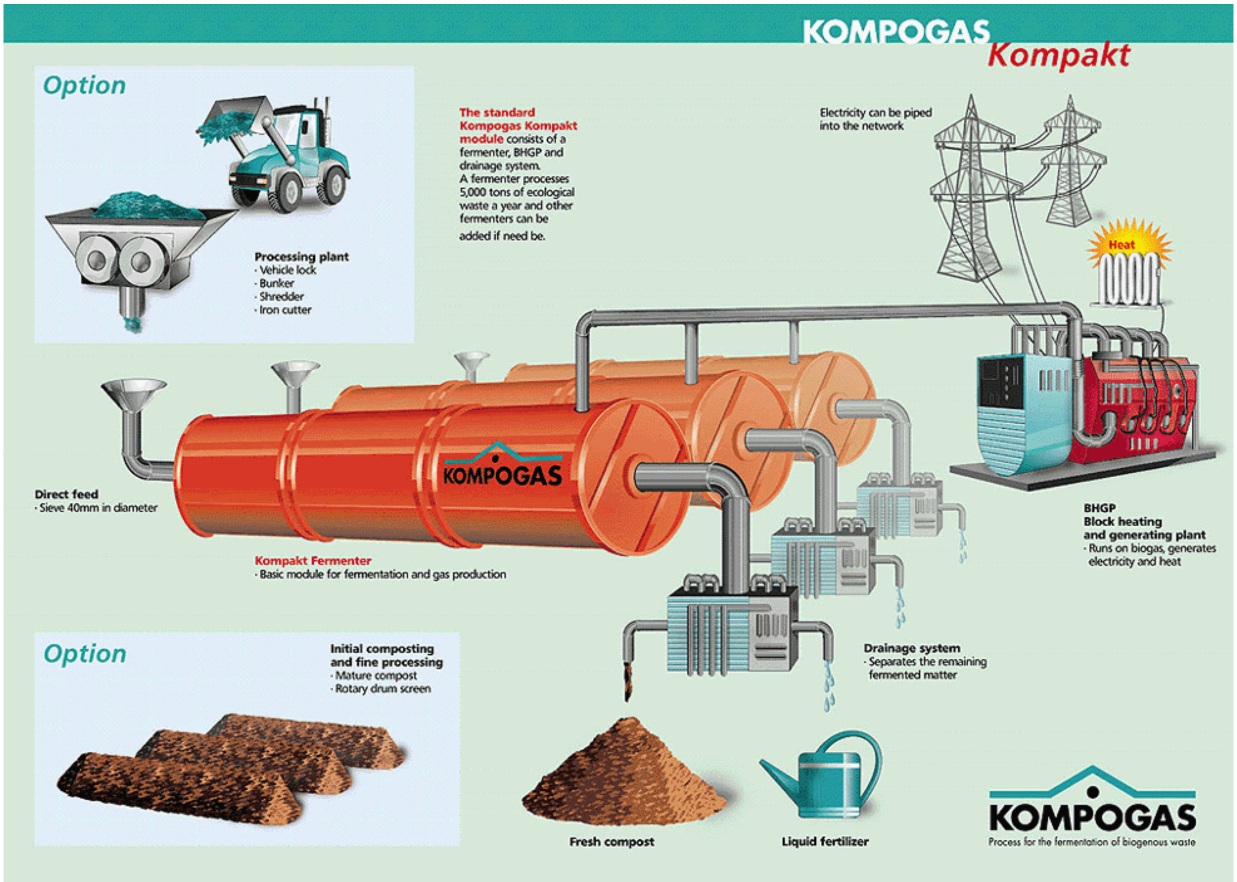

Figure 15. Overview of the Kompogas process
From the company website, accessed September 2007.

Multi-Stage Digesters

When evaluating multi-stage digesters, care must be taken in understanding the goal of using more than one reactor. In some cases multiple digesters are operated in parallel, such as at the Valorga plant in Varennes-Jarcy and the Biocel plant in Lelystad, the Netherlands. These are, in fact, not multi-stage digesters. Each reactor is a separate single-stage digester. This may be done because of tank size limitations, to simplify management, or to expand capacity of an existing plant. A true multi-stage digester applies different conditions to the reactors in each stage. The difference can be in the OLR of each stage, the presence or absence of oxygen, the introduction of an intermediate treatment, or the overall reactor configuration. Many different combinations of factors are possible.

Figure 16 depicts a generic two-stage AD system with hydrolysis occurring in a high-solids first stage and methanogenesis occurring in the low-solids second stage (dry-wet configuration). In other systems, such as the Scharting-Uhde process, both stages are low-solids (wet-wet configuration) [35].

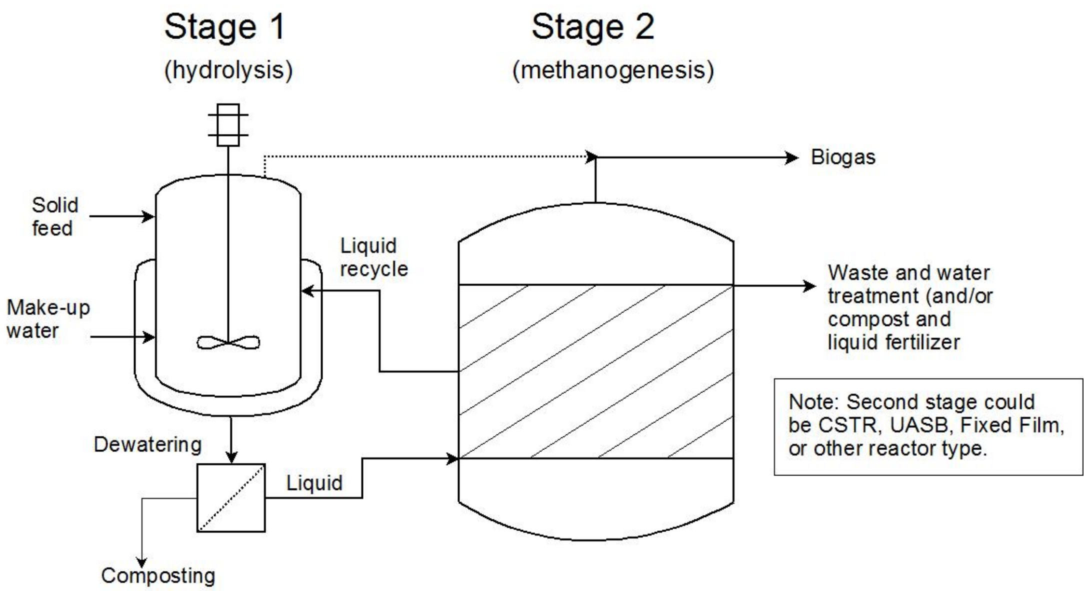

Figure 16. Schematic of a generalized two-stage anaerobic digestion system

As mentioned earlier, there are relatively few commercial, operational multi-stage AD units. It was expected that more of the multi-stage systems would be in operation by now due to their higher loading rates, improved process stability, and flexibility, but the added complexity and presumed expense of building and operating commercial multi-stage systems have so far negated the yield and rate enhancements [35]. Nonetheless, the potential of multi-stage digesters to improve performance has prompted much research, and a few notable commercial multi-stage digesters have been successful. Some of these use multiple stages for reasons other than separating acidogenesis from methanogenesis.

Biotechnische Abfallverwertung GmbH & Co. KG (BTA)[11]

Developed in Germany and applied (via several licensing companies) throughout Western Europe and in select locations in Canada and Japan, the BTA system is one of the oldest and most successful in terms of the number of existing operational digesters [44]. Although small units are single-stage, the majority of the BTA digesters are large (>100,000 MT/yr [110,000 tons/y]) multi-stage, wet-wet units [51, 52].

The multistage BTA digester utilizes a pulper and hydrocyclone much like those employed by the Waasa single-stage digester. Pulped and density-fractionated MSW passes through a solid/liquid separation unit and leachate is passed directly to a methanogenesis reactor (see Figure 17). Solid extract is mixed with process water to bring the MC to 75 percent and then pumped into a hydrolysis reactor with a residence time of 4 days [52]. Hydrolysis leachate is then transferred into the methanogenesis reactor which has a 2d HRT. Dewatered digestate is then either treated aerobically or disposed. Installations with a designed capacity of less than 100,000 MT/y (110,000 tons/y) often utilize the pulper as the hydrolysis tank, eliminating one step in the process.

[11] For detailed description of the BTA process, see http://www.bta-technologie.de/files/process-general.htm.

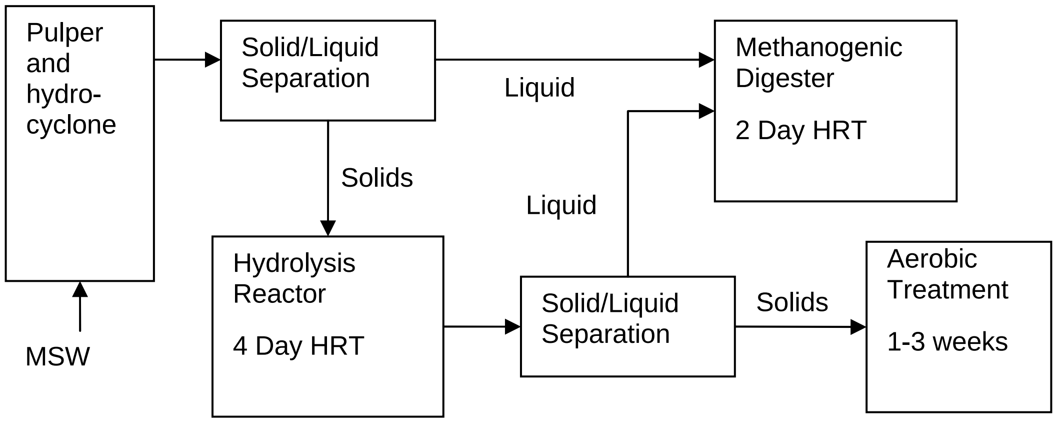

Figure 17. Diagram of the BTA multistage digestion process
Adapted from a BTA short information brochure [52].

Data from a Canadian installation indicate biogas yields of 0.12-0.15 m^3/kg (3.8-4.6 scf/lb).[12] Although the report did not indicate specifically whether the yield was in terms of wet tons or tons of VS, this range is typical for yield per wet ton. No data for TS or VS composition was given, but the compost composition was 30 percent TS, 70-75 percent VS (most likely recalcitrant, indigestible cellulose and lignin) and the N:P:K ratio was 71:13:16 which is nitrogen rich for a land additive.

Linde-KCA-Dresden GmbH

Linde-KCA has built wet and dry digesters since 1985 and currently has eight digesters operating in Germany, Portugal, Spain, and Luxembourg, both wet and dry, mesophilic and thermophilic [50]. The typical dry digester is operated in two stages. The first stage is aerobic and the hydrolysis product is transported via conveyor to a horizontal plug-flow digester with internal rotors for mixing and transporting solids to the dewatering unit [44]. Although this is a two-stage system, the first stage could also be considered an aerobic pretreatment stage apart from the anaerobic digester since it is not anaerobic. Nevertheless, the digester is capable of handling 15-45percent TS and generates roughly 0.10 m^3/wet kg (3.2 scf/wet lb) of biogas.

[12] Data taken from Canada Composting Inc's web site: http://www.canadacomposting.com/performance_data_2.htm.

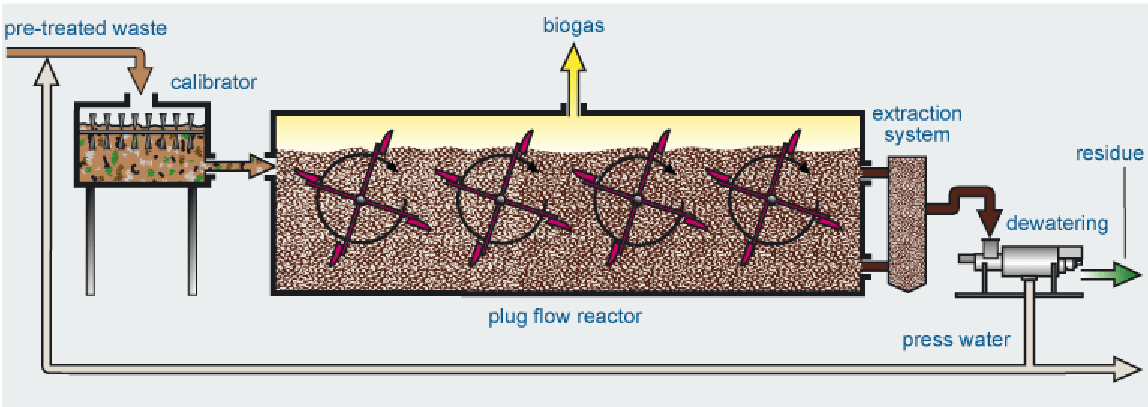

Figure 18. Linde-KCA two-stage dry digester
From the Linde-KCA website, accessed September 2007.

Super Blue Box Recycling (SUBBOR)

In 1999 the Canadian Minister of Industry and Technology Partnership Canada sponsored Super Blue Box Recycling Corp., a subsidiary of Eastern Power Limited which owns and operates two large landfill-gas fueled power plants, to develop the Super Blue Box Recycling process.[13] The technology was reported to have progressed from the lab to a 25,000 MT/y (27,500 tons/y) pilot plant [43], but the project was reported to be stalled due to legal difficulties [53]. Most AD processes use aerobic post treatment to stabilize undigested organic material, but the SUBBOR process uses an interim steam treatment between two digestion stages in an attempt to more completely degrade the MSW (see Figure 19). Non-digestible material is manually removed from the incoming MSW stream and the resulting stream is milled prior to loading into the first digester [43].

In lab studies, the first digester was operated in batch configuration at thermophilic conditions for 35-60 days with landfill leachate added to bring the solids content to 25 percent (w/w) [54]. The digestate was then placed in a steam explosion unit for 5 minutes at 55-62 bar (800-900 psi), 220-270 °C (430-520 °F) and then replaced into the batch digester for an additional 12-24 days under the same conditions as the initial digestion. This enhanced the biogas yield by 40 percent and resulted in a fine, "peat-like" mass of residual solids [43, 54]. The available literature does not specify how the pilot and full-scale process is configured. Vogt et al. (2002) recommended that the initial AD treatment last 25 days but suggested that the retention times could be adjusted as needed to lend flexibility to the process.

One of the primary advantages of the technology is the high quality of the treated solids when used as a planting medium. The extended length of digestion and additional financial and energy costs of the pressurized steam treatment unit are potential disadvantages, but some of these costs could be offset by the additional biogas production and higher price earned for the peat-like end product. The company website claims a four-year payback on investment with operating and capital costs in the range of \$50-100/MT (\$45-90/tons).[14]

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[13] Information from http://pages.interlog.com/~estrnpwr/subbor/index.htm, accessed on Sept. 17, 2007.

[14] From http://pages.interlog.com/~estrnpwr/subbor/advantages.htm
and http://pages.interlog.com/~estrnpwr/subbor/Brochure3.htm, accessed on Sept. 17, 2007.

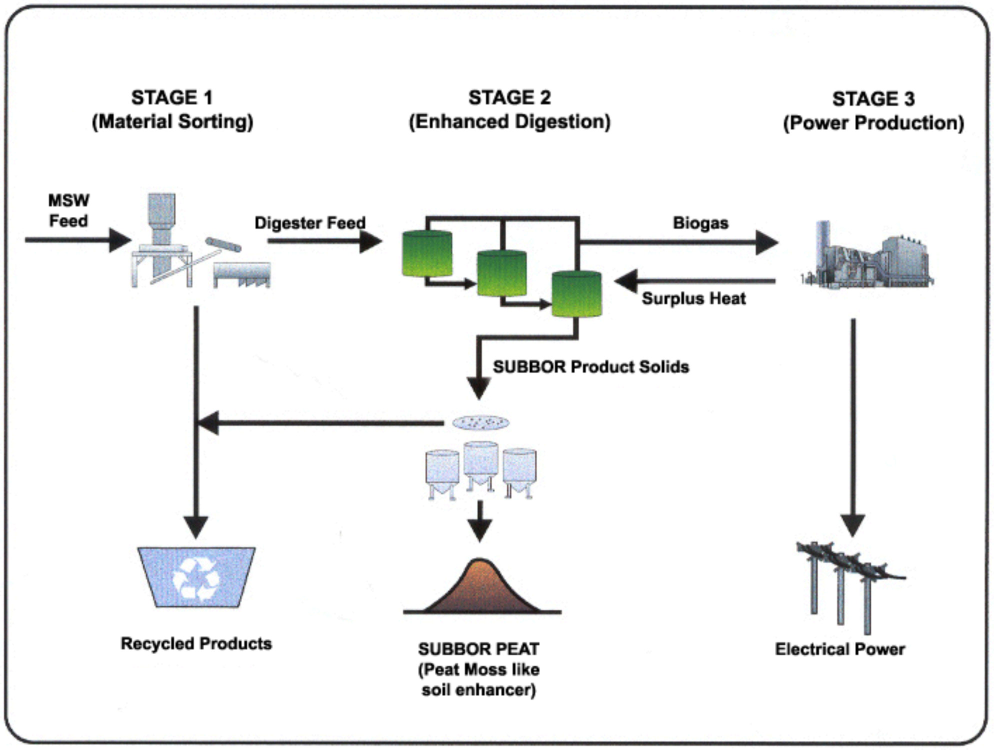


Figure 19. Simplified flow diagram of the two-stage SUBBOR anaerobic digestion process.
From the SUBBOR Corporation website, accessed February 2008.

WEHRLE Umwelt GmbH (Biopercolat)

The Biopercolat process is a dry-wet, two-stage process [35, 47]. The first hydrolysis stage is carried out under partial aerobic conditions with high solids content (see Figure 20). Process water is continually percolated through the hydrolysis reactor—a horizontal tunnel that slowly rotates in order to slightly aerate the mixture and prevent clogging and channeling [35]. The leachate passes on to the second-stage fermentation reactor—an anaerobic plug flow filter filled with support material operating at mesophilic temperature. After two to three days in the percolator, the solids are separated and transferred to an enclosed tunnel composter. The liquid fraction is transferred to the fermentation reactor, and displaced liquid is partly recirculated back through the percolator and partly aerated for disposal as wastewater.[15]

[15] From http://www.wehrle-umwelt.com, accessed on Feb. 14, 2008.

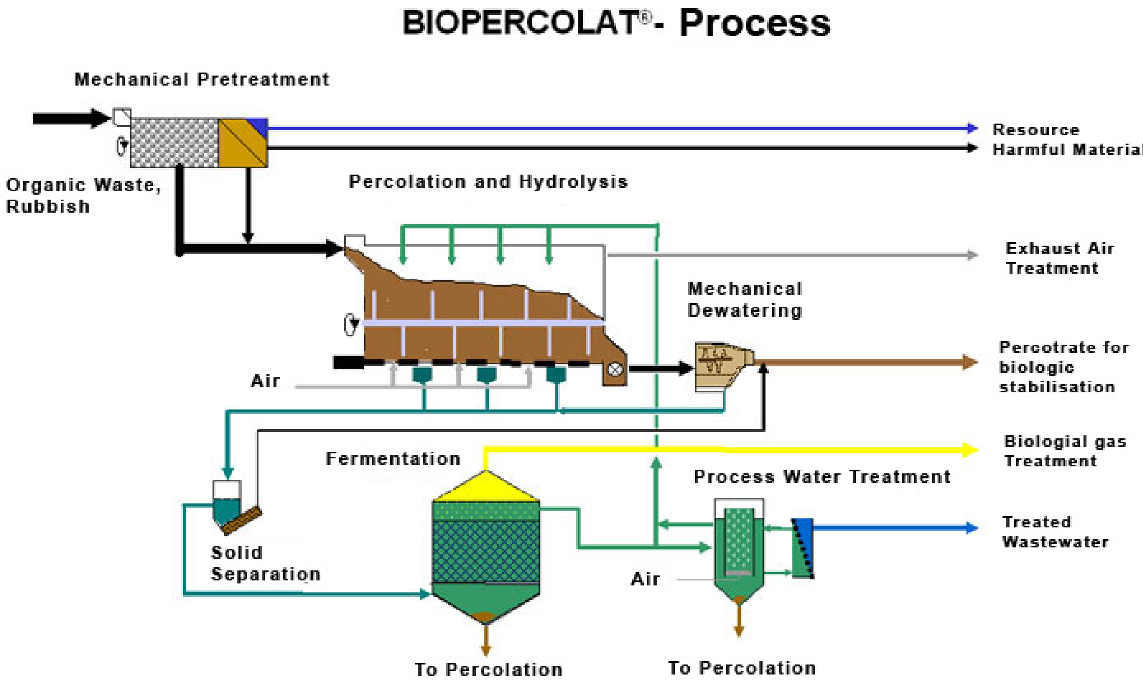


Figure 20. Schematic waste-flow diagram of the two-stage Biopercolat process
From the WEHRLE Umwelt GmbH website accessed February 2008.

Batch Digesters

Some of the first dry digesters were envisioned as modified landfills [55]. This resulted in the creation of batch systems that recycled leachate in a manner similar to landfill bioreactors. However, unlike landfill bioreactors the batch digester conditions were more carefully controlled and as a result biogas production rates were higher and retention times were lower [35]. The primary disadvantage of batch digesters is uneven gas production and lack of stability in the microbial population. Sequential and phased batch digesters attempt to surmount these disadvantages, and preliminary lab experiments have revealed complex population dynamics in these systems resulting in the ability to separate useful fermentation products such as hydrogen and organic acids.

Biocel

The Biocel system was developed in the 1980s and 1990s in Holland at the Wageningen University as a part of the early research on high-solids digestion of MSW [55-57]. The initial goal of the system was to reduce cost by simplifying material handling and eliminating the need for mixing while simultaneously achieving relatively high loading and conversion rates. Success with the lab-scale system led to construction of a pilot 5 m^3 (1,000 gal) reactor by the early 1990s which was used for more extensive testing of start-up, heating, and leachate recycling [56]. By 1997 a full-scale 50,000 MT/y (55,000 tons/y) plant consisting of a digester and enclosed post-digestion aeration beds had been built in Holland to treat SS-OFMSW [57].

Currently the Dutch company Orgaworld owns and operates the Biocel plant along with several tunnel composting facilities and one AD facility also in the Netherlands[16]. The company plans to increase electricity production to >10 million kWh/y by treating up to their permitted 85,000 MT/y (94,000 tons/y).

Figure 21. Biocel leach-bed batch digester facility in Lelystad, Netherlands
From the Orgaworld website, accessed September 2007.

While batch systems may simplify material handling, they sacrifice control over the biological processes. Because a batch is loaded all at once, the internal conditions change as microbial populations shift in response to the consumption of waste and production of intermediate metabolites. A lag phase occurs as organic polymers break down followed by a sudden drop in pH as organic acids are produced from the hydrolysate [55, 58]. If this pH drop is too severe, methanogenesis cannot occur. In a lab study, even after 100 days, only hydrogen and CO_2 were produced [58][17].

The initial lab and pilot studies attempted to mitigate this effect by mixing the incoming feed with digestate from a previous batch, using aerobic pre-treatment, adding buffers, changing the inoculation rate, and altering the leachate recycling rate [55, 58, 59]. At the pilot scale the maximum achievable OLR was 7 kg VS/m^3/d (0.058 lbs/gal/d) [56] which is similar to continuous high-solids digesters (see Table 6. Published biogas yields for full-scale digesters treating a variety of wet OFMSW types.

Reference	Plant	Location	Average Biogas Yield	
			(m3/kg)	(scf/lb)
[114]	Valorga	France	0.144	4.61
		Netherlands	0.93	2.98
		Germany	0.127	4.07
[41]	Valorga	Italy	0.180	5.77

16 Orgaworld website: http://www.orgaworld.com/indexgb.html, accessed Sept. 17, 2007.

17 Incidentally, hydrogen content reached 30 percent after 10 days and remained at that level for over 20 days. Transient bio-hydrogen production could potentially be an advantage of batch digestion systems that some companies are developing (see http://www.onsitepowersystems.com/biohydrogen.html).

		Italy	0.60	1.92
		France	0.145	4.65
		Netherlands	0.92	2.95
		Germany	0.126	4.04
	Dranco	Germany	0.147	4.71
		Belgium	0.103	3.30
		Austria	0.135	4.32
[31]	BTA (wet process)	Germany	0.92	2.95
[104]	Kompogas	Switzerland	0.90	2.79
	ISKA	Germany	0.40	1.28
Overall Average			0.112	3.60

), but at full-scale the average OLR was 3.6 kg VS/m^3/d (0.030 lbs/gal/d) which is closer to the OLR of low-solids systems.

Another advantage of batch systems is the low water input requirement. However, during lab and pilot-scale studies it was found that no leachate drained from the waste when the TS content was higher than 35 percent, and methanogenesis was inhibited by lack of contact between bacteria and substrate [56]. In comparison, continuous high-solids systems achieve stabile digestion at 25-35 percent TS. However, the relatively low moisture content of the feedstock makes it more difficult to heat. It was found that loading cold feed and allowing it to slowly reach the target temperature resulted in doubling the digestion time required at the pilot scale [56]. Therefore cold feed has to be preheated.

The full-scale Biocel system is comprised of fourteen 720 m^3 (190,000 gal) leach bed reactors, each loaded in 480 m^3 (130,000 gal) batches keeping the pile 4 m (13 ft) high to avoid excessive compaction [57]. Reactor temperature is kept at 35-40 °C (95 -104 °F) by heating leachate which is sprayed over the pile. The digester retention time is 21 days and the post-treatment aeration bed retention time is 1-3 weeks. At full-scale, a complex system of vacuums and pumps from the generator exhaust system flushes oxygen out of the headspace and captures odors when opening digester doors for loading and unloading [57]. Fresh MSW is sorted manually and loaded by shovel without any pretreatment for size reduction or screening. For each MT (1.1 tons) of MSW loaded, the system produces 70 kg (150 lbs) of biogas, 120 kg (265 lbs) of water vapor, 500 kg (1100 lbs) of compost, and 230 kg (510 lbs) of wastewater [57]. At the pilot scale, the biogas yield was 0.70 m^3/kg wet waste (2.2 scf/lb) which is lower than typical (see Table 6) but no comparison has been made with continuous systems using the same feedstock [56].

Even though the Biocel system requires 40 percent less capital investment than continuously fed digesters [35], no further Biocel plants have been built since 1997 and batch digesters hold only a very small share of the European AD market. This could be due to the willingness of the European marketplace to invest in higher rate and yield digestion, perhaps because of financial support for renewable energy production and space limitations. Biocel units require ten times as much space as continuous dry digesters [35]. The cost savings may be more important for the U.S. market where capital and operating costs have been shown to have a much larger influence than biogas yield on financial tenability [50]. Also, space limitations are not generally seen as a significant factor in the U.S.

Sequential Batch Anaerobic Composting (SEBAC)

The SEBAC system was developed in the early 1990s at the University of Florida with the goal of eliminating mixing and minimizing handling while maintaining high conversion rates and system stability [60-63]. Similar to the Biocel process, the SEBAC system consists of two- or three-batch, leach-bed reactors with leachate recirculation by sprayer, but unlike the Biocel system, the SEBAC digesters are loaded in sequence such that leachate can be transferred between reactors.

OFMSW is roughly chopped to 10cm and placed in a batch reactor. Leachate from a mature reactor is sprayed onto the fresh material and recycled to the top of the pile until methanogenesis stabilizes. The reactor is then switched over to internal recirculation until methane production slows as the batch matures (see Figure 22). In theory this allows organic acids to be applied to mature reactors with active methanogenic populations, and it allows the microbes from mature reactors to be sprayed on fresh waste as an additional inoculant. In practice, the dynamics of leaching are not well understood, thus the system appears to be difficult to control.

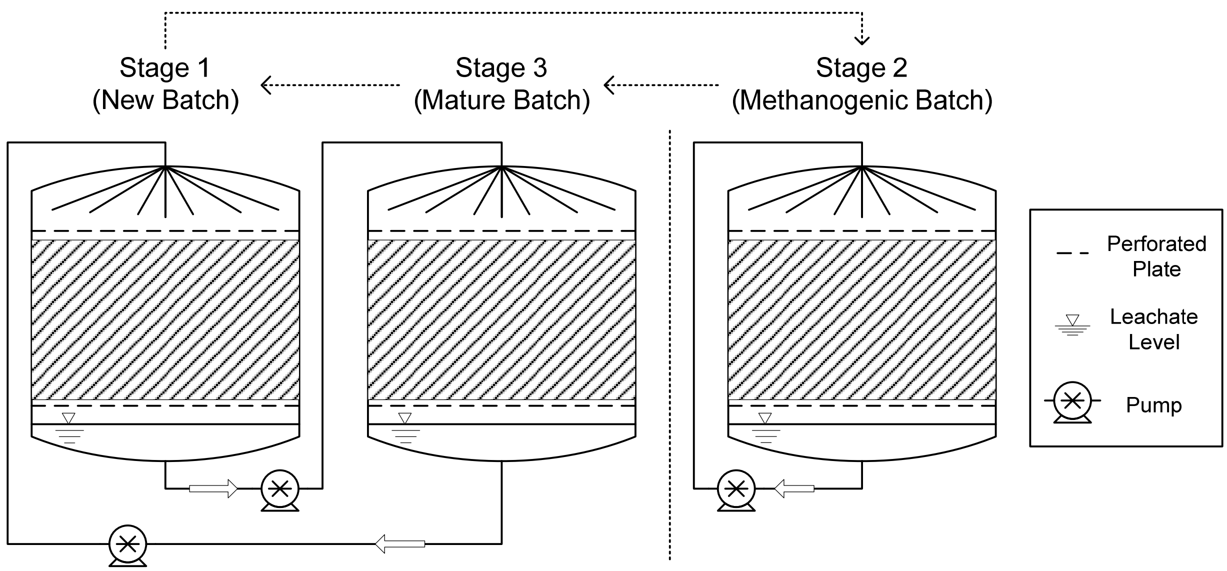


Figure 22. SEBAC process diagram
Adapted from Chynoweth [61].

At the lab scale, the SEBAC process had difficulty starting when loaded with pure food waste [63]. Bulking agents were required to prevent compaction and allow leachate to drain through the pile. However, even with the most successful startup scheme, the highest biogas production rate was not achieved until 50-60 days after loading. It was not clear from this study what the overall methane yield was, but an earlier pilot scale study reported yields of 0.16 and 0.19 m^3 CH_4/kg VS (2.6 and 3.0 scf/lb) with retention times of 21 and 42 days respectively [61]. This is much lower than published thermophilic methane yields for continuous digesters treating OFMSW (see Figure 29). The waste stream contained 60 percent paper and cardboard, 10 percent plastic, and 6 percent yard waste, and the authors reported that the yields represented 80–90 percent of the ultimate methane potential. However, it appears that large quantities of paper and plastic were required to allow proper leaching. No known full-scale SEBAC systems have been built but research on the system continues. A new design (SEABAC II) tailored for the low gravity environment of manned space missions reduced the volume requirement by 60 percent by eliminating the headspace and intentionally wetting and compacting the feedstock, which also allowed for forced leachate pumping [64]. The prototype SEABAC II digester operating at 35°C (95 °F) was able to ultimately achieve a methane yield of 0.3 m^3 CH_4/kg VS (4.8 scf/lb VS) in about 14 days from a mix of rice, paper, and dog food.

Anaerobic Phased Solids (APS) Digester

Like the SEBAC system, the APS Digester uses batch loading to stimulate rapid organic acid production in a two-stage digester system. However, the APS Digester system avoids the problems caused by using leach bed reactors by combining high-solids reactors for the first stage with a low-solids mixed biofilm reactor in the second stage [65, 66]. The high-solids reactors are loaded in phased batches, and the leachate from the batch reactors is continuously circulated through a single low-solids digester. In theory, batch loading simplifies material handling, and because the hydrolysis reactors are high-solids digesters, they can handle relatively large inorganic contaminants. Leachate recirculation prevents solids from fouling the wet methanogenesis reactor. Because the batches are phased, the leachate contains a relatively constant concentration of organic acids.

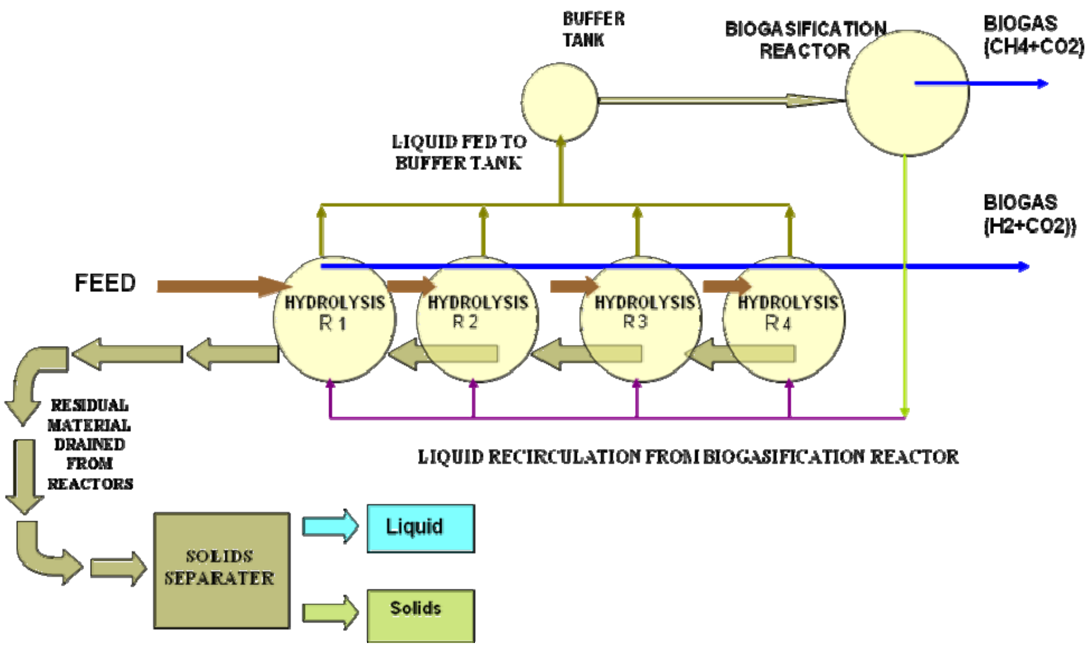


Figure 23. Schematic diagram of the APS Digester system.

A pilot demonstration plant for the APS Digester system with a capacity of about 1-2 tons (dry) per day of organic waste has been under development at the University of California, Davis (Figure 24 and Figure 25). It was undergoing full capacity commissioning at the time of this publication.

The pilot plant consists of five 38 m^3 (10,000 gal) vertical steel cylindrical tanks. The four hydrolysis tanks possess hot water jackets for heating the reactor contents. The methanogenesis tank is heated via thermal heat exchange with a natural gas/biogas powered boiler. The system was designed to operate at both mesophilic and thermophilic temperatures. Fresh feedstock is loaded via a chopper pump and hydraulic ram system and mixing is accomplished using high-velocity liquid jets. The gas collection system was designed to separately collect hydrogen-rich biogas from the hydrolysis reactors. System operators can monitor and control the digesters via remote computer system. The overall design objective was to build a low maintenance, yet flexible, two-stage system with no internal moving or custom-built parts.

Figure 24. APS Digester technology pilot demonstration plant (front view)
UC Davis

Figure 25APS Digester technology pilot demonstration plant (rear view)
UC Davis

In laboratory studies, the system was able to digest rice straw with a lingo-cellulosic content (lignin, cellulose and hemicellulose) of 85 percent and achieve 40-60 percent solids reduction with a biogas yield of 0.4-0.5 m^3/kg VS (6.4-8.0 scf/lb VS) which is on par with yields seen for much more highly degradable substrates [65]. Laboratory studies have been conducted with other substrates as well such as food waste, OFMSW, food processing wastes, and animal manure (personal communication, Ruihong Zhang, UC Davis, CA, Feb. 15, 2008). The biogas yields from the food waste collected from restaurants and green waste (grass clippings) were 0.60 and 0.44 m^3/kg VS (9.6 and 7.0 scf/lb VS), respectively with 12 day solids retention in the digesters [67].

BioConverter

The BioConverter digester is a single-stage, sequentially batched system. However, in its full-scale application, an equalization tank was used for pulping and metering feed into the batch reactors and it has been reported that the pH of this tank dropped, indicating that it may serve as a first-stage hydrolysis reactor [68]. The original pilot system consisted of eight 380 m^3 (100,000 gal) biofilm reactors with simultaneous gas and liquid recycling [68]. Performance and operational details were unavailable for the system,, but it was one of the first full scale digesters treating municipal food waste in the U.S. It was shut down in March 1999 due to odour control problems [68].

History of Full-Scale AD of MSW

The anaerobic digestion of solid waste has evolved into an international industry with significant investment in research and development. Although the U.S. does not currently have an operational full-scale plant for AD of MSW, many pilot projects have been conducted and lessons have accumulated.

The global experience with commercial AD of MSW was also reviewed. The industry continues to evolve rapidly. The following discussion attempts to objectively and thoroughly describe the progression and current state of commercial AD of MSW. Several previous discussions with the same goal were consulted during the review process.

Demonstration Plants and Proposed Commercial Digesters in the U.S.

In the 1930s, Harold Babbitt and his team of researchers at the University of Illinois investigated AD of garbage and sewage sludge. Babbitt postulated that garbage may one day be dumped directly into the sewer system, i.e., via in-sink garbage disposal units [69], and in a forward-looking study ran numerous small and large scale tests on batch and continuous digesters at the Illinois Engineering Experiment Station [70]. Table 5 summarizes Babbitt's experiments.

Table 5. Summary of 1936 University of Illinois garbage digestion research [70].

Experimental Design	Purpose	Findings
Bench scale batch	Determine optimal ratio of garbage to sewage sludge	At least 10% sludge required for seed Batch quickly acidifies
Standard Imhoff digester	Evaluate material handling and gas production of typical sewage sludge digester Compare solid and ground garbage	Material handling problems with solid garbage Biological problems with ground garbage
Medium scale two-stage anaerobic digester	Evaluate anaerobic digestion of garbage/sludge mixtures	Can digest garbage High biogas yields Requires temperature control
Small continuous stirred-tank digester	Measure BOD load of effluent Evaluate effect of garbage elutriation during sewer transport Calculate scale up digester size	Digester effluent will not overly stress treatment plant Elutriation increases specific BOD and reduces gas production, but does not affect overall digestion or methane content
Large continuous stirred-tank digesters	Study effect of adding chemicals to control pH	Lime works better than sodium hydroxide for correcting pH
Bench scale batch	Study digestion of "lumps" of garbage	Lumps of garbage cause sudden pH drops upon disintegration Batch digesters can over time recover from acidification

Experimental Design	Purpose	Findings
Bench scale batch	Study AD of pure food substances Compare AD of sugar, starch, oil, cellulose, and protein	Cellulose exhibited a longer lag phase than other substances Sugar and starch are similar and easily inhibited by acidification Oil causes scum buildup that slows digestion Protein is inhibited independent of pH (probably by ammonia)

Testing began with 1.5 L (0.4 gal) batches to determine the optimal ratio of ground garbage to sewage sludge. They then loaded an 8.2 m (27 ft) high single-stage digester with solid and ground garbage. The solid garbage caused clogging problems, formed a scum layer, and bypassed the chamber completely. Ground garbage caused rapid pH drops, and it was decided that fresh garbage should be pre-mixed with digester liquid in a dosing tank. Subsequently they built a two-stage digester in which the 4.9 m^3 (1,290 gal) first stage was integrated into the 18.1 m^3 (4,770 gal) second stage (see Figure 26). Temperature was held at 31-33 °C (88-92 °F). With an OLR of 0.2-1.0 kg VS/m^3/d (0.002-0.008 lbs VS/gal/d) and HRT of 30 days they were able to sustain digestion with gas yields of 0.5-0.75 m^3/kg VS (8-12 scf/lb VS). They found that gas production changed as solids moved from the first to the second stage by gravity and that oil and grease floated.

They then ran experiments that determined that adding 0.60 kg/m^3 (2.5 tons/million gal) garbage to the sewers would at most double the BOD load after the garbage had been eluted during transportation in the sewer mains. Based on these results, it was calculated that 80.6 L/person (21.3 gal/person) of digester would be required, assuming a disposal rate of 0.10 kg VS/person/d (0.23 lb VS/person/day). Because their early attempts to digest garbage resulted in souring and material handling difficulties, they also studied pH control and looked more carefully at how lumped garbage breaks down. They found that garbage had to be ground in order to be digested. They also studied digestion of sugar, starch, protein, and oil separately at a range of OLR, thereby demonstrating how these different foodwaste components are inhibited differently.

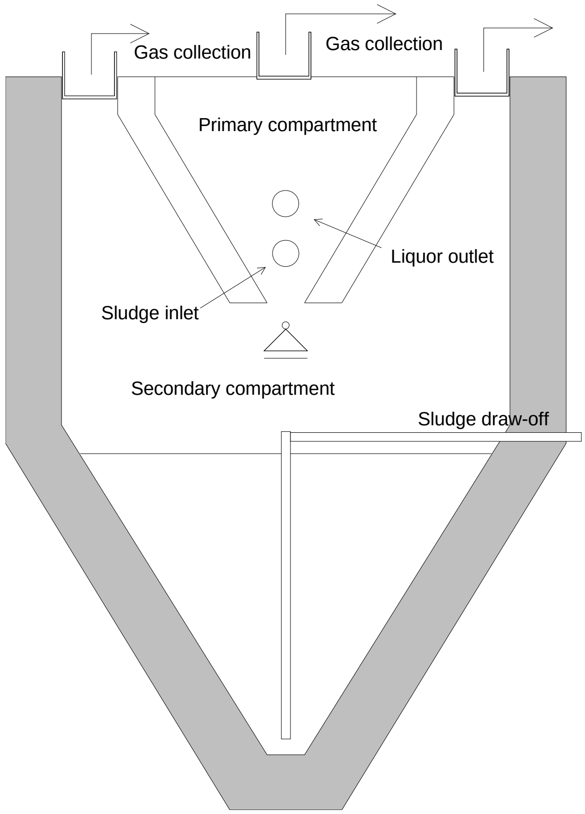


Figure 26. Experimental two-stage garbage digester
Developed at the University of Illinois in 1936 [70].

In the 1970s a pilot MSW digestion facility was built in Pompano Beach, Fla., which became known as the Refuse Converted to Methane (RefCoM) project [71]. The National Science Foundation and Department of Energy funded the project. The Gas Research Institute conducted the project, and Waste Management, Inc. was contracted to build the digestion system [71-74].

The digester was a single-stage, low-solids, complete-mix reactor with mechanical mixing and no heating. An auger was used to feed the mechanically separated MSW into the tank. The 30,000 MT/y (33,000 tons/y) plant included a material processing facility for milling and screening the waste, followed by density separation in a hydrocyclone. No post-digestion processing was incorporated.

This pilot project operated for ten years before being shut down and discontinued due to poor performance [75]. The most significant problems encountered involved the material handling equipment. The shredders and screw presses frequently became clogged. Large textiles and plastic material caused the formation of heavy balls that either clogged the feeding and sorting mechanisms or placed heavy loads on the mechanical mixers in the digester. These difficulties led to inconsistent feeding, incomplete degradation of larger particles, solids accumulation and low biogas production (about 0.16 Nm^3/kg VS) [75]. The resulting evaluation of the technology was unfavorable, but many of the problems described above have been addressed to some degree by systems that evolved in Europe. Nonetheless, there will likely be material handling and processing difficulties with any system that processes MSW.

In the 1980s the Gas Technology Institute, University of Florida, and Walt Disney World experimented with a novel digester design that was “non-mixed and employed passive settling and flotation to concentrate solids” [76]. Called SOLCON (for “solids-concentrating”), the system achieved a solids retention time (SRT) that was about three times longer than the HRT which increased overall solids conversion compared to that of a complete-mix digester [76-78]. The SOLCON work at Walt Disney World led to the development of a proprietary system for converting MSW to high purity methane as a natural gas substitute. The multi-stage digester consisted of a leaching bed followed by a two-stage acidogenesis/methanogenesis system in which air was used to strip CO_2 and H_2S from the biogas and the oxygen-rich effluent was recycled back through the digester [79, 80]. The details of the system’s operation and performance data were not published.

In the 1980s and early 1990s, researcher David Chynoweth and collaborators at the University of Florida developed a multi-stage leachbed anaerobic composting process for anaerobic digestion of high-solids organic feedstocks. Called Sequential Batch Anaerobic Composting (SEBAC), batches of high-solids wastes are digested in sequence using leachate recycled from a batch in a later stage of decomposition [60-63]. Based on experience gained from the SOLCON project, the SEBAC design was intended to eliminate mixing and minimize handling while maintaining high conversion rates and system stability. The SEBAC system was similar to earlier high-solids and multi-stage designs [81-85]. Currently, the SEBAC system is being adapted to serve as the “principal component in a bio-regenerative solid waste management system” for long-term manned space missions (i.e. manned missions to Mars) [86, 87].

In the 1990s a pilot two-stage digester was tested at the Illinois Institute of Technology on sewage sludge mixed with the MSW processed by a material recovery facility in Madison, Wisconsin, which consisted of 72 percent paper, food, and garden waste [75]. The digester consisted of an inclined 76 L (20 gal) first stage followed by a vertical 230 L (60 gal) packed-bed reactor for the second stage. The pilot system was operated in various modes at a range of OLR from 2.4 to 7.5 $kg/m^3/d$ (0.02-0.06 lbs/gal/d) and HRT from 7 to 13 d, resulting in methane yields of 0.138-0.222 m^3/kg VS (2.21-3.56 scf/lb VS).

According to the McElvaney Associates Corporation website,[18] a 3,785 m^3 (1 million gal) digester built in Waimanalo, Hawaii, treating 60,000 MT/y (66,000 tons/y) of cow and chicken manure, began treating 12,000 MT/y (13,000 tons/y) of food waste and fat in the 1990s. The system, called BioConverter, was redesigned in the mid-1990s and a 660 MT/y (700 ton/y) pilot system was built in Kihei, Hawaii. The system was continuously fed a mix of food, green, and paper waste from 1995-1997. The pilot plant ceased operations when the original financing organization, Sustainable Technologies Inc., changed owners and the new owner refused to continue financing the plant [88].

In 2004, the cities of Los Angeles and Lancaster, Calif., approved contracts with BioConverter LLC to build a 900,000 MT/y (990,000 tons/y) and 66,000 MT/y (73,000 tons/y) version of the system, respectively [88]. Construction was slated to be completed by this year (2008).

The original Waimanalo system consisted of a 265 m^3 (70,000 gal) equalization tank which served as a combined sorting/hydrolysis stage from which slurry was pumped into eight 380 m^3 (100,000 gal) suspended-growth reactors [68]. The pumping action helped mix the reactor contents. Solids were separated and combined with yard trimmings and enough liquid effluent to

[18] http://www.bioconverter.com, accessed on Feb. 12, 2008.

maintain the proper moisture content in open windrows for composting. The remaining liquid effluent was held in an open lagoon and used as a liquid fertilizer. Initially, the operators faced hurdles hauling wet foodwaste and educating clients to separate foodwaste from contaminants.

Once the foodwaste collection system was streamlined, legal and regulatory problems began plaguing the system. Odors from the open lagoon and windrows drew complaints and legal action from neighbors. New regulations were drafted specific to anaerobic digestion, and several new permits were required at great cost. In conjunction with rising property taxes and a change of ownership, this ultimately resulted in the permanent closure of the plant in 1999 [68]. The redesigned system uses vertical tanks with combined slurry and gas mixing and will incorporate a membrane filter for recycling the CO_2 through the digester and using the methane as a natural gas substitute [88].

A 30 MT/y (33 tons/y) pilot digester was built at UC Davis in 1993 by Microgen Corporation of Ithaca, N.Y. It was designed to be operated on a synthetic mix of food waste and yard waste [3, 89]. The digester was a complete-mixed, thermophilic, high-solids reactor, consisting of a 2.25 m^3 (594 gal) tank with mechanical mixing, loaded with 33-43 kg/m^3/d (0.28-0.38 lbs/gal/d) wet weight or 10-14 kg VS/m^3/d (0.08-0.12 lbs VS/gal/d). This plant was primarily a research facility funded by the California Energy Commission and the Prison Industry Authority (PIA) of the State of California. The authors were able to demonstrate successful continuous operation in a high-solids system producing 0.75 m^3/kg VS (12 scf/lb VS) of biogas when adding manure and dewatered wastewater sludge. They also found that the MSW they tested lacked key nutrients needed for sustained biogas production, and these nutrients could be provided by adding both manure and sludge [3, 90].

In 1993 Folsom Prison installed and began operation of a 33,200 MT/y (36,500 tons/y) MSW sorting facility with the intention of anaerobically digesting and composting the organic fraction along with wastewater biosolids [91]. According to a 1994 BioCycle article, construction of a 3,000 m^3 (790,000 gal) thermophilic digester began in June of that year and completion was scheduled for 1995 [91]. The biogas was intended to power a fuel cell operated by the Sacramento Municipal Utility District (SMUD).

In 1997, a short BioCycle update claimed that the sorting station was receiving more than 90 MT/d (100 tons/d) mixed solid waste and composting the yard trimmings and organics [92]. The article reported that they expected completion of the anaerobic digester in 1998, but it did not elaborate on the reason for the delay. The program faced some financial and security difficulties, the former related to the state's failure to honor a contract for payment of the prisoners used for manual labor on the sorting line [93, 94]. No further mention of the digester could be found in the literature, and in 2004 the MSW sorting program was suspended [95]. The digester project was stalled due to administrative problems rather than any shortcoming in the digester itself, and the Sacramento Municipal Utility District has begun looking for partners to continue the Folson Prison AD project (personal communication, Marco Lemes).

UC Davis researchers continued testing newer and larger digester designs throughout the 1990s until building the 5,000 MT/y (55,000 tons/y) pilot Anaerobic Phased Solids (APS) digester system beginning in 2004 with funding provided by the California Energy Commission and private industry [65, 66, 96, 97]. The APS system was officially launched in October 2006 when testing began. A feasibility study for the construction of a full scale 11,000 MT/y (12,000 tons/y) APS digester for the treatment of OFMSW at California State University, Channel Islands was also conducted, but the authors of the feasibility study concluded that the project should be postponed until the technology had been proven at the pilot scale [50].

The National Renewable Energy Laboratory (NREL) also tested a high-solids, thermophilic digester design in the late 1980s and 1990s [98-102]. NREL designed a tubular plug-flow digester similar to the high-solids systems currently popular in Europe but with mechanical mixing via slowly rotating blades (1 rpm). A screw augur was used for loading the feed which consisted of a mixture of OFMSW, industrial food processing waste, and sewage sludge.

In 1996 construction began on a pilot 1,000 MT/y (1,100 tons/y) plant in Stanton, Calif. [102]. The system was initially designed to treat fish waste and MSW in American Samoa, but was ultimately sited near a fish processor in Southern California after reviewing the cost of transporting the system. Several organizations and private contractors coordinated on various phases of the project, including a thorough safety review, permitting, construction, testing, and start-up. Operation was delayed due to mechanical and biological difficulties. After refining the initial design, adding an automated control system, and waiting for the thermophilic microbial culture to acclimate and stabilize, the plant began operating at the beginning of 1998. Within three months, however, operations ceased due to funding issues.

A number of problems delayed operation of the system at Stanton, primarily related to mixing and temperature control [102]. The mechanical mixers which worked well at the lab scale needed substantial re-design at the pilot scale. The solids content also had to be reduced by diluting with water. This led to leakage problems, difficulties managing the increased amount of effluent, and diminished OLR due to the need to maintain an HRT of at least 14 days, all of which reduced the conversion efficiency. In their laboratory studies, NREL found that feed TS content needed to be maintained at >55 percent. The effect of the mechanical problems was exacerbated by administrative difficulties in coordinating between vendors, contractors, and sponsor organizations. Involving too many institutions inhibited management of the project.

There were a number of biological problems as well. The initial seed bacteria lost viability while the mechanical problems were being fixed. This slowed the shift from mesophilic to thermophilic temperature. The low OLR and HRT caused by dilution of the feed also reduced the ability of the bacteria to metabolize organic matter. Another unanticipated problem at the pilot scale was ammonia build-up. In lab tests, the system handled ammonia concentrations as high as 5000 parts per million (ppm), but the pilot system maxed out at 10,000 ppm which inhibited the bacterial consortium. To solve the problem, the carbon to nitrogen ratio (C/N) of the feedstock was increased by adding waste paper and cardboard. This reduced ammonia levels to 1000 ppm and biological activity resumed.

Despite these problems the system was successfully operated for several months during which OLR was raised from 5 to 14 kg VS/m^3/d (0.04 to 0.12 lbs VS/gal/d). During this period methane yield ranged from 0.249-0.348 m^3/kg VS (3.99-5.57 scf/lb VS). The VS reduction was above 80 percent at most OLR. Methane content averaged 57 percent and the system proved to be resilient at a wide range of OLR. Odors were also kept low and the automated control system worked well.

In 2001, city planners in Nashville, Tennessee, rejected a proposal from Waste Recovery Systems, owners of the Valorga process, to build an integrated garbage disposal system with AD for electricity production. The size of the system was not mentioned, but developers claimed that it would provide two-thirds of the energy produced by the solid waste combustion plant operating at the time. The plant would have cost $50 million and was prepared to charge the city $30 per MT ($27 per ton) of garbage treated. The proposal was rejected in favor of a “transfer and disposal” plan which would transport the garbage out of the county [103].

A 2004 feasibility study by the consulting agency RW Beck concluded that the installation of an anaerobic digester to treat solid waste in Linn County, Iowa, could be financially viable [104]. In a report to the Iowa Department of Natural Resources, the Bluestem Solid Waste Agency (with RW Beck) reviewed solid waste AD technologies in Europe, collecting survey data on the performance of the systems in order to model the financial performance of a 60,000 MT/y (66,000 tons/y) and a 30,000 MT/y (33,000 tons/y) plant. They found that the larger plant would be the most financially viable and would produce 1 MW of electricity. Siting and permitting issues were seen as the primary inhibiting factors. The report noted that federal programs were not likely to fund the project and the project managers would need to arrange financing before pursuing the project. This may indicate a common roadblock facing new waste treatment technologies, which must be approved by planning commissions charged with mitigating public financial risk.

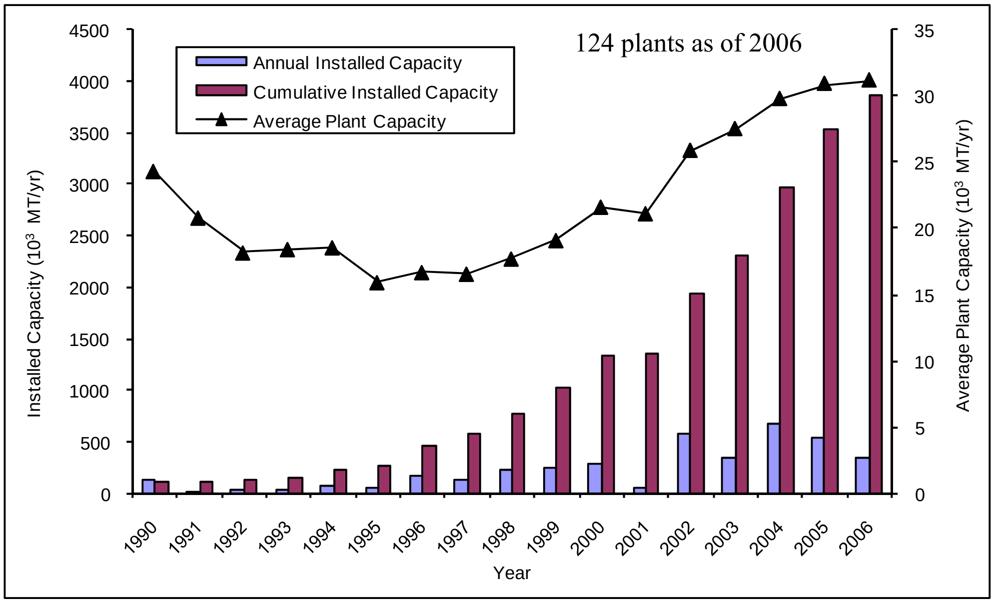
In 2005, the Sacramento Municipal Utility District investigated the feasibility of converting garden waste from Sacramento and the surrounding areas to energy using AD [105]. The feasibility study found that potentially 236,000 MT (260,000 tons) of garden waste were available for conversion. The study screened 13 commercially available digesters, including two American systems, and chose the Kompogas, Dranco, Valorga and Linde KCA digesters based on the track record of the technologies and manufacturers. Cost estimates for 45,000 MT/y, 91,000 MT/y, and 180,000 MT/y (50,000 ton/y, 100,000 ton/y, and 200,000 ton/y) wet and dry digesters were compared, and they concluded that the digester should be co-located with a landfill, composter, or material recovery facility (MRF) to reduce costs and simplify permitting. The study also noted that including foodwaste with the garden waste would increase the biogas production.

International Commercial Developments in AD of MSW

Europe

Anaerobic digestion and aerobic composting of kitchen, food processor, and garden wastes is well established in Europe. This result is largely due to waste and energy policies in Europe (e.g., The Landfill Directive). By the end of 2006, there were some 124 anaerobic digester plants with capacity greater than 3,000 MT/y (3,300 tons/y) treating feedstock composed of at least 10 percent MSW. The combined capacity was 3.9 million MT/y (4.3 million tons/y) [29]. [19] This is twice the number of plants and four times the capacity that existed in 2000 [29, 48]. The recent trend has been toward larger digesters (see Average Plant Capacity in Figure 27). Average digester size declined between 1990 and 1995 as developers were faced with problems in scaling up what were previously only lab- and pilot-scale systems. As technologies advanced and experience accumulated in managing larger systems, the average digester size increased from 1995 to 2004. The average size of the 52 plants installed in the period from 2001-2005 was 43,000 MT/y [29].

[19] This excludes thousands of manure and sludge digesters that co-digest smaller amounts of food and household wastes or energy crops (there are about 3300 farm-based biogas production plants in Germany).



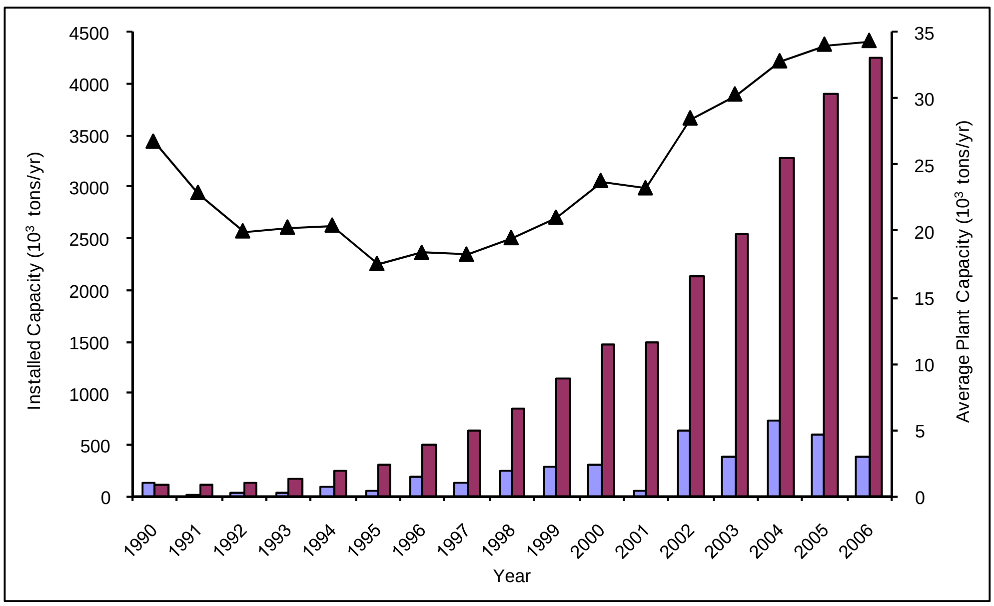


Figure 27. Solid waste anaerobic digester capacity in Europe

Figures are provided in SI (top) and English (bottom) units. Annual installed capacity for 1990 includes all years prior to 1990; all other years include only new installations. Average plant capacity provides an indication of the number of plants in operation [29].

Despite the increased use of AD, about 3 percent of biodegradable solid waste in Europe is treated anaerobically. Aerobic composting remains the primary means of OFMSW biological treatment in Europe (treating about 7 percent of household organic wastes) [29, 48]. Spain, Belgium, Holland, Switzerland and Germany had the largest per capita AD capacities as of 2006. It was estimated that Spain treated about 10 percent of its organic waste using anaerobic digesters (see Figure 28) [29]. A number of companies design and build anaerobic digesters for the European market (see Table 1). The International Energy Agency and the California Integrated

Waste Management Board maintain databases of firms active in processing MSW with anaerobic digestion technology.[20]

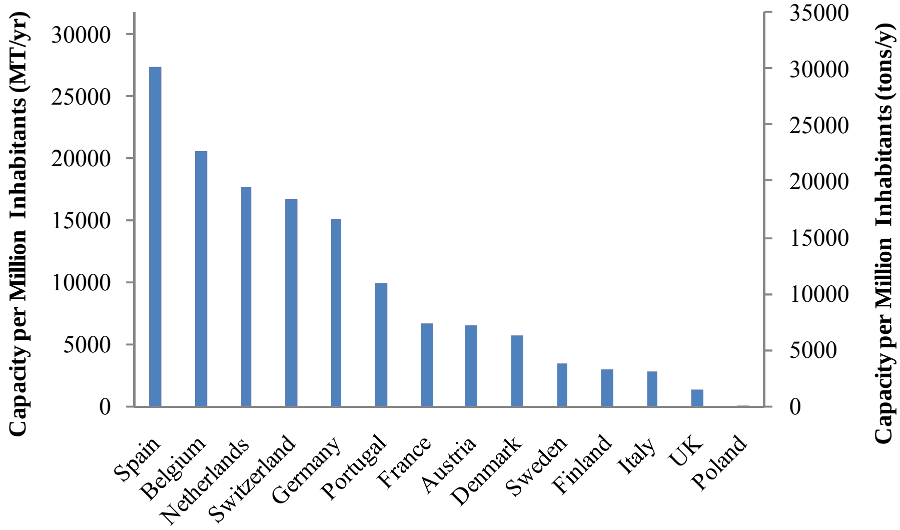


Figure 28. Anaerobic digester capacity by country
Amounts are based on an assumed organic waste production of 300 kg/person/y (331 lbs/person/y) [29].

Canada

There has been interest in recent years in biological treatment of MSW in Canada due primarily to new waste management plans in Montreal and Toronto [43, 106-109]. Montreal has put into place a plan to recycle 60 percent of the current 5.8 million MT/y (6.4 million tons/y) MSW going to landfill [109]. This will mean composting 167,000 MT/y (184,000 tons/y) of OFMSW and 270,000 MT/y (297,000 MT/y) of yard waste. As a result, the literature reports that several new digesters were built in the past 10 years.

Near Toronto, Ontario, a full-scale demonstration of a novel 25,000 MT/y (27,500 tons/y) two-stage plant known as the SUBBOR process—designed to produce a high-quality peat—was built in 2000 [43]. In 2002, the city of Guelph withdrew funding from the project and became involved in a legal battle with the SUBBOR Corporation that had not been settled as of the time of this publication [53].

Two plants based on the BTA model--a 25,000 MT/y (27,500 tons/y) plant in Toronto and a 150,000 MT/y (165,000 tons/y) plant in Newmarket, Ontario--were operating in Canada as of 2004 [110]. That year the larger of the two was acquired by Halton Recycling Ltd., an on-site composting operation was built, and throughput was reduced to 30,000-40,000 MT/y (33,000-44,000 tons/y) [111, 112]. Wright Environmental Management is a company based in Ontario that has built in-vessel tunnel composting systems in Scotland, England and the U.S., amounting to over 70,000 MT/y (77,000 tons/y) of MSW treatment capacity [110].

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[20] Databases of AD vendors were found at http://www.iea-biogas.net/plantlistlist.htm, http://www.ciwmb.ca.gov/organics/conversion/Vendors/.

Australia

In Australia, the New South Wales government and Sydney city planners established landfill reduction policies in 2000 that led to the installation of a 170,000 MT/y (187,000 tons/y) ISKA Percolation AD facility in 2003 with 2.2 MW of electrical generating capacity [110, 113]. According to the company website, the plant began operations in 2004 and was expanded in 2006 to accept 225,000 MT/y (248,000 tons/y) of unsorted waste[21]. A 35,000 MT/y (38,500 tons/y) wet digestion facility built with BTA components also began digesting commercial waste and wastewater treatment sludge in Parramatta/Sydney in 2003, according to the BTA-Technologies website[22]. ArrowBio also recently built a 90,000 MT/y (99,000 tons/y) two-stage wet digester in Sydney as part of the South West Sydney Council Resource Recovery Project[23].

Japan

CiTec has built four Waasa anaerobic digester systems in Tokyo, Ikoma, Shimoina, and Jouetsu which together treat over 20,000 MT/y (22,000 tons/y) of OFMSW and dewatered wastewater sludge [110]. Kompogas also built a 20,000 MT/y (22,000 tons/y) plant in Kyoto in 2004 (see Table 4).

Others

Valorga installed a 90,000 MT/y (99,000 tons/y) facility in Tahiti and was reported to be planning installation of a 55,000 MT/y (60,500 tons/y) plant in India, but the latter project has not been confirmed [110].

An Israeli environmental services firm called Arrow Ecology has patented a novel MSW separation process coupled with a two-stage digester called ArrowBio, which Santa Barbara and Coachella Valley in California were considering adopting in the early 1990s [106]. Arrow Ecology installed an 80,000 MT/y (88,000 tons/y) version of the facility in Tel Aviv in 2002 that produces 2-3 MW of electricity [110]. ArrowBio systems have also been scheduled to be built in Australia, Mexico, and Scotland.

Kompogas installed a 20,000 MT/y (22,000 tons/y) facility in Martinique in 2005[24].

EcoTec of Finland was reported to be planning installation of a 55,000 MT/y plant in India based on the WABIO design, but the project has not been confirmed [110].

Entec Biogas GmbH of Austria reported that they were planning to build a 150,000 MT/y (165,000 tons/y) BIMA digester with 5 MW electrical capacity to treat MSW from Lucknow, India[25].

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[21] ISKA Percolation company website: http://www.iska-gmbh.de/en/index.php, accessed on Feb. 12, 2008.

[22] BTA-Technologies website: http://bta-international.de/, accessed on Feb. 13, 2008.

[23] ArrowBio website: http://arrowbio.com/, accessed on Feb. 13, 2008.

[24] Kompogas website: http://www.kompogas.com, accessed on Feb. 13, 2008.

[25] Entec Biogas GmbH website: http://www.entec-biogas.at/en/index.html, accessed on Feb. 13, 2008.

Two new Valorga digesters are being built in China, a 270,000 MT/y (290,000 tons/y) plant in Shanghai and a 105,000 MT/y (115,000 tons/y) plant in Beijing[26]. India and China have an extensive history of digesting rural farm and household waste using low tech AD systems. It would not be surprising to see more AD of MSW facilities appearing there in the future as the countries develop their infrastructures.

[26] Valorga International website: http://www.valorgainternational.fr/en/page8.xml, accessed on Feb. 13, 2008.

Digester Performance

Biogas Yield

Digester performance depends greatly on reactor configuration and OFMSW source [114]. Many reports in the literature indicate performance of MSW digesters in terms of biogas yield per wet weight of MSW treated (see Table 6). Full scale plants typically achieve biogas yields of 0.10–0.15 m^3/wet kg (3.2 to 4.8 scf/wet lb). However, comparisons of systems based on yield per wet weight MSW assume consistency of MSW and biogas composition. Biogas can contain from 50-70 percent methane by volume, too wide a range for accurately estimating energy potential. Methane yield is more useful than biogas yield but requires accurate CO_2 or CH_4 detectors or expensive lab tests (i.e. gas chromatography). Also MSW can vary widely in MC and digestibility, based largely on the amount of paper, grass, wood, and other lignocellulosic material contained.

Therefore the scientific literature typically reports yield in terms of methane yield per dry weight of volatile solids. This assumes that volatility is a proxy for biodegradability, but lignocellulosic material tends to be less biodegradable than other volatile compounds. A better proxy for biodegradability is the five-day biological oxygen demand (BOD-5), but the standard method for measuring the BOD-5 content of a feedstock takes too long to be used for measuring the ongoing biogas yield of a digester, thus it is rarely reported in the literature. Therefore, when comparing systems treating different MSW streams, one must be careful to take note of compositional differences.

Table 6. Published biogas yields for full-scale digesters treating a variety of wet OFMSW types.

Reference	Plant	Location	Average Biogas Yield	
			(m^3/kg)	(scf/lb)
[114]	Valorga	France	0.144	4.61
		Netherlands	0.93	2.98
		Germany	0.127	4.07
[41]	Valorga	Italy	0.180	5.77
		Italy	0.60	1.92
		France	0.145	4.65
		Netherlands	0.92	2.95
		Germany	0.126	4.04
	Dranco	Germany	0.147	4.71
		Belgium	0.103	3.30
		Austria	0.135	4.32
[31]	BTA (wet process)	Germany	0.92	2.95
[104]	Kompogas	Switzerland	0.90	2.79
	ISKA	Germany	0.40	1.28
Overall Average			0.112	3.60

In addition, biogas yield says nothing about the rate of methane production. Reactor efficiency is more important than overall yield for determining financial performance of a system. The overall biogas production rate and the MSW throughput rate, or organic loading rate, are important determinants of a system's efficiency. For comparing system efficiencies, compositional feedstock differences are important.

The maximum achievable OLR, however, is highly dependent on reactor configuration. High temperature reactors are commonly referred to as high-rate reactors because of the increased reaction rate. Two-stage reactor configurations were developed in order to increase the achievable OLR. Increasing the OLR often leads to disproportionate increases in organic acid production due to biological growth rate and pH tolerance differences between acid producing and acid consuming microbes. An upper limit on OLR seems to exist at around 15 kg VS/m^3 (0.125 lbs VS/gal), but the achievable OLR can be greatly affected by the overall digestibility of the waste. The biogas or methane production rate in itself is not very useful because it depends on the loading rate, but by combining the OLR and biogas yield the reactor efficiency can be determined in terms of biogas production rate per unit of reactor volume.

Comparing the performance of industrial scale OFMSW digesters treating different waste streams is difficult, especially since companies tend to protect performance data. Generalizations have been attempted in the literature, such as those shown in Figure 29 which shows the average biogas yield at a given OLR for a large number of lab, pilot, and full scale studies [115].

The efficiency of a digester in terms of gas production per unit digester volume can be calculated by multiplying the OLR by the biogas yield. Hence it can be seen that even though wet digestion of SS-OFMSW at 55°C (130°F) achieved a biogas yield of about 0.8 m^3/kg VS (12.8 scf/lb VS), the OLR was only 2 kg VS/m^3/d (0.02 lbs VS/gal/d) and the biogas production rate was only 1.6 m^3/m^3/d (0.21 scf/gal/d). For comparison, the mesophilic digestion of food waste resulted in much lower biogas yields of 0.45 and 0.3 m^3/kg VS (7.2 and 4.8 scf/lb VS), but at OLR of 6 and 9 kg VS/m^3/d (0.05 and 0.075 lbs VS/gal/d) the biogas production rate was 2.7 m^3/m^3/d (0.36 scf/gal/d) which is 70 percent higher. Based on this analysis, dry digestion of "kitchen waste + paper" had the highest biogas yield per unit reactor volume closely followed by dry thermophilic digestion of OFMSW from a pilot scale study using simulated OFMSW composed of paper, yard and food waste. Most of the reactors studied exhibited biogas production rates in the range of 1.5-3.5 m^3/m^3/d (0.20-0.47 scf/gal/d). All of the digesters studied that produced more than 3.0 m^3/m^3/d (0.4 scf/gal/d) biogas were thermophilic. Although many of the data used for the Hartmann and Ahring review [115] came from laboratory experiments, it gives an indication of the range of performances to be expected from full-scale systems.

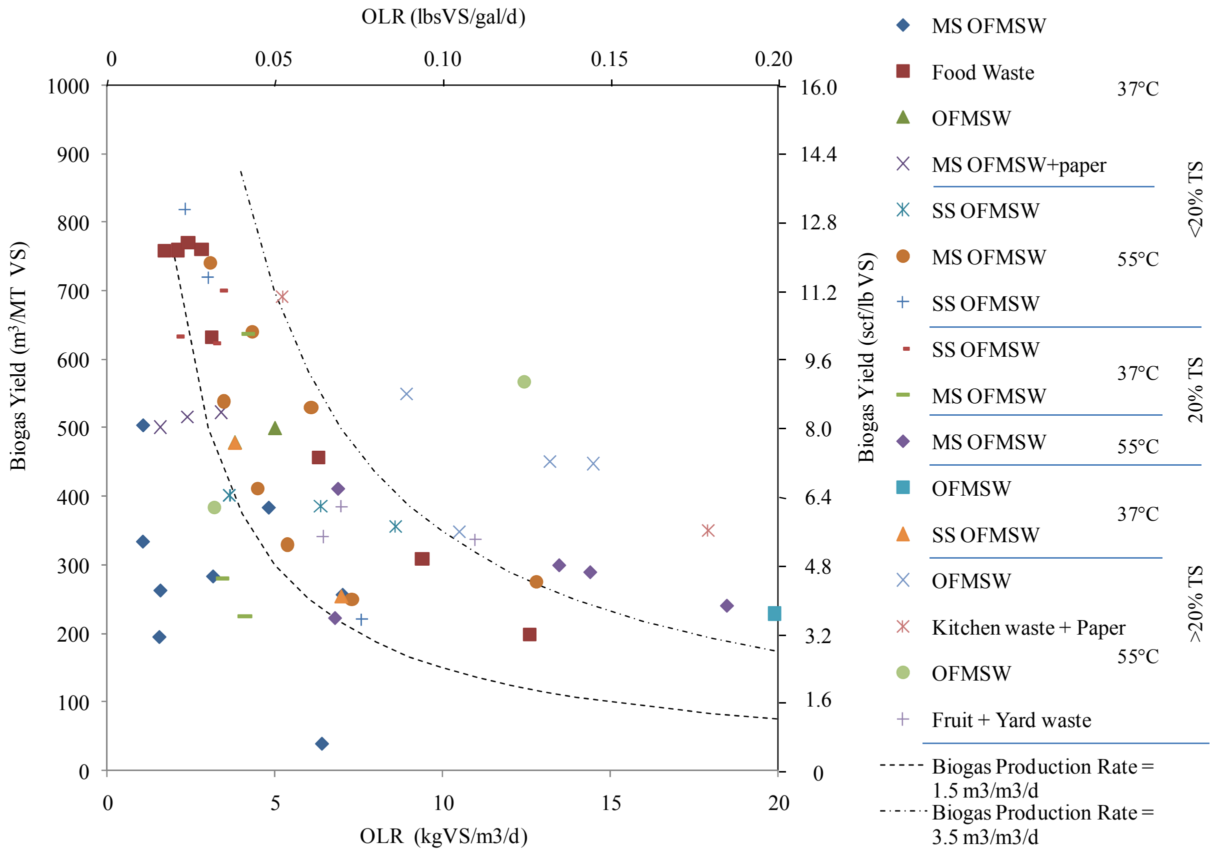

Figure 29. Biogas yield as a function of organic loading rate
Amounts are for lab, pilot, and full scale OFMSW digesters in metric and standard units [115].

It can be seen in Table 6. Published biogas yields for full-scale digesters treating a variety of wet OFMSW types.

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Overall Average			0.112	3.60

that for single-stage digesters, HRT ranges from 9-30 days, with the average for thermophilic reactors being 66 percent that of mesophilic digesters (10-16 vs. 15-25 days) [26]. No clear difference exists between wet and dry digesters in terms of HRT, but the obtainable OLR is about three times higher for dry digesters and two times higher for thermophilic digesters. The achievable OLR for SS-OFMSW is about 65 percent that of MS-OFMSW, which is to be expected since the higher digestibility of SS-OFMSW leads to greater acidification of the digester.

Table 7. Reactor conditions typical of single-stage OFMSW digesters.

Temp	Substrate	TS	Min HRT	Max HRT	Min OLR	Max OLR
Mesophilic			**15.1**	**24.9**	**3.8**	**5.9**
	MS		**15.3**	**26.7**	**4.9**	**7.0**
		Dry	17.0	30.0	6.0	9.0
		Semi-Dry	15.0	20.0	6.0	8.0
		Wet	14.0	30.0	2.6	4.0
	SC		**14.5**	**19.5**	**3.5**	**5.0**
		Dry	17.0	25.0	4.0	6.0
		Semi-Dry	12.0	14.0	3.0	4.0
	SS		**15.5**	**27.5**	**2.5**	**5.0**
		Dry	17.0	25.0	4.0	6.0
		Wet	14.0	30.0	1.0	4.0
Thermophilic			**10.8**	**16.2**	**6.6**	**12.4**
	MS		**9.0**	**17.5**	**7.5**	**17.5**
		Dry	12.0	20.0	9.0	15.0
		Semi-Dry	6.0	15.0	6.0	20.0
	SC		**12.0**	**16.0**	**6.0**	**9.0**
		Dry	12.0	16.0	6.0	9.0
	SS		**12.0**	**15.0**	**6.0**	**9.0**
		Dry	12.0	16.0	4.0	6.0
		Semi-Dry	12.0	14.0	8.0	12.0
Grand Total			**13.3**	**21.3**	**5.0**	**8.6**

MS = mechanically sorted
SC = food service industry source separated
SS = residential source separated
HRT = hydraulic retention time (d)
OLR = organic loading rate (kg VS L-1 d-1).
Adapted from Cecchi et al [26]

One full-scale wet digester in the literature was reported to reach OLRs comparable to those typical of high-solids dry systems ([31]). The digester was designed to accomodate 8,000 MT/y (8,800 tons/y) but was initially accepting 7,200 MT/y (8,000 tons/y). After a study demonstrated that a lab-scale digester could sustain OLR as high as 15 kg COD/m^3/d (0.125 lbs COD/gal/d), the full-scale digester's loading rate was increased to 12,000 MT/y (13,000 tons/y). The lab study initiated the digester at an HRT of 20 days and reduced the HRT to 5.7 days in 5 steps (20-13-10-8-7-5.7) of roughly 15-20 days each. Whenever HRT was reduced, OLR was increased by adjusting the amount of extra water added to the feed. A maximum OLR of 15 kg COD/m^3/d (0.125 lbs/gal) was sustained in the lab for 45 days with consistent biogas production of 50-60 L/d (1.8-2.1 scf/d). In addition to biogas production, VFA, VS reduction, and pH were monitored to ensure that digestion was stable. COD reduction and biogas yield both increased linearly with OLR at the lab scale.

Upon successful completion of the lab study, loading rate of the operating full scale digester was increased from 8 to 15 kg COD/m^3/d (0.067-0.125 lbs COD/gal/d) stepwise over two months. The digester was run for five months at 15 kg COD/m^3/d (0.125 lbs COD/gal/d) with an average biogas production rate of 4.5 m^3/m^3/d (0.6 scf/gal/d). The study demonstrated that a low-solids system could be loaded at higher OLR than typical for such systems, although these results may not necessarily generalize to other systems. More importantly, the study showed that if the same feedstock and reactor conditions are used in the lab and at full scale, the lab results can be used to reliably predict the full-scale system performance.

Life Cycle Analysis

Anaerobic digesters are environmentally friendly but often cost more than alternative treatment technologies. However, wise management decisions take whole-system evaluations of technology options into account. The standard method for performing such analyses is the life cycle assessment (LCA) methodology outlined in ISO 14040 of the International Standards Organization.

The LCA methodology begins with defining the scope and boundaries of the system under consideration followed by an inventory analysis and impact assessment. The outcome of an LCA is specific to the system under consideration, but if many analyses have similar outcomes generalizations can be made with caution. Decision models have been developed based on LCA results for making solid waste management decisions [116]. A thorough analysis of these modeling efforts is beyond the scope of this report but should be taken into consideration by policy makers and solid waste management developers. Here, a brief review of some of the LCA findings for AD and other OFMSW treatment technologies is provided.

Several authors have investigated the overall environmental and economic impacts of anaerobic digestion using the LCA methodology [20, 30, 117, 118]. All of the studies found that AD produced less air and water pollution than aerobic composting or landfilling of OFMSW.

A Canadian LCA compared AD, open windrow composting, and landfilling of MSW where landfills with and without energy production were included [118]. The report found that AD produced less air and water pollution than any of the other technologies (see Table 8). The study also found that over the life of the project, AD had a positive net energy balance, while the other technologies—including landfilling with gas collection—consumed net energy.

However, the study did not seem to account for the embodied energy of construction or transportation. For example, additional transportation would be required for an AD facility located at a centralized site some distance from the landfill. A centralized digester, however, would serve multiple landfills. The costs and benefits of centralized OFMSW treatment would have to be evaluated for the entire region.

The model also assumed that excess electricity could be sold to the local power grid. The study did include emissions from post-digestion treatment of residuals, and the reductions in emissions due to AD were high (see Table 8). Interestingly, open windrow composting led to an increase in air and water pollution for most pollutants as compared with landfilling. This would most likely change if in-vessel composting were considered.

Table 8. Comparison of the energy use and emissions from anaerobic digestion (AD), open windrow composting (WC), and landfilling without energy recovery (LF)
(All emissions are air emissions with the exception of lead, which is a water pollutant.) Adapted from Haight [118].

	Metric Units			Standard Units		
	AD vs. LF	**AD vs. WC**	**WC vs. LF**	**AD vs. LF**	**AD vs. WC**	**WC vs. LF**
Energy Consumption (GJ/y and mmBTU/y)	-400,000	-430,370	+32,228	-380,000	-407,910	+30,546
GHG Emissions (MT/y and tons/y CO_2 eq.)	-121,908	-84,795	+38,170	-134,379	-93,470	42,075
NOx (MT/y and tons/y)	-48.8	-50.3	+1.5	-53.8	-55.4	+1.7
SOx (MT/y and tons/y)	-68.4	-74.6	+6.21	-75.4	-82.2	+6.83
PM-10 (MT/y and tons/y)	-58.4	-50.8	-7.6	-64.4	-56.0	-8.4
VOC (MT/y and tons/y)	-8.6	-3.8	-4.7	-9.5	-4.2	-5.2
Lead (kg/y and lbs/y)	-88.3	-93	+4.72	-194.7	-205.0	+10.4

Conversely, a Swiss LCA comparing AD with aerobic composting and incineration revealed that greenhouse gas (GHG) emissions were similar for the biological processes, including three different AD configurations and enclosed and open aerobic composting [20]. The greenhouse gases considered included methane, carbon dioxide, ammonia, nitrous oxide, and hydrogen sulfide. The authors noted that methane emissions were higher than expected for all of the technologies. This was attributed to post-digestion processing for AD and insufficient aeration for aerobic composting (open windrow composting was found to produce less methane than enclosed composters), which points to the need for careful handling of post-digestion solids in order to avoid emissions. The overall environmental impact analysis included emissions due to the treatment process and land application of the resulting compost as well as energy consumption. The anaerobic technologies evaluated performed better overall than incineration and composting on a whole-system basis, but open composting performed better than incineration and enclosed composting (see Figure 30). The enhanced performance of the Kompogas system was most likely due to the filtration of the post-treatment gas.

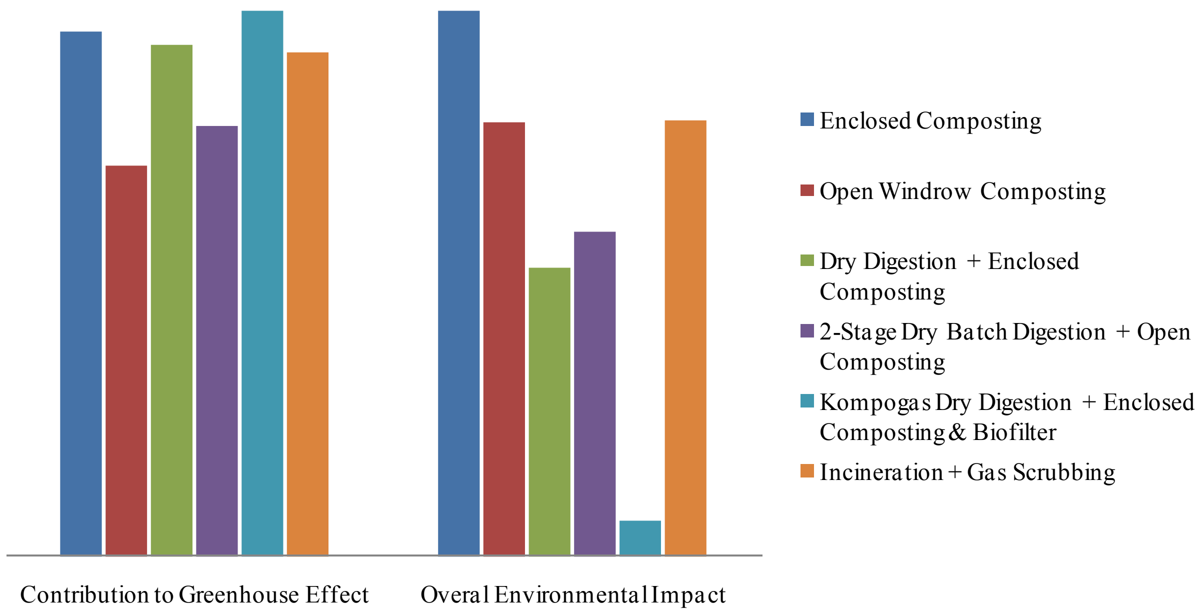

Figure 30. Greenhouse effect contribution and overall environmental impact of 10,000 MT/y (11,000 tons/y) biogenic waste treatment.
Lower bars indicate less impact. Scores scaled to percent of maximum. Adapted from Edelmann [20].

In Germany, where air and water emissions are strictly controlled, biofilters are widely used to scrub the exhaust from both compost and AD with post-treatment aeration [30]. Air emissions from composting were found to be higher than they are from AD of MSW, but the wastewater produced was seen as problematic in the study by Fricke et al [30]. A Swedish study also found that AD was preferable to composting (the authors did not specify the mode of composting or the basis of their calculations) based on environmental impact and energy consumption [117].

A Turkish study compared five waste treatment scenarios applicable to the region, one of which incorporated AD [119]. The remaining scenarios involved a variety of material recovery facilities and source separation of organics for home composting (which was considered outside the system boundaries for the analysis). In this study, the need for transporting waste from collection sites to the appropriate treatment facility greatly influenced the energy consumption and emissions of the scenario. This, along with the additional sorting required for AD, led to increased energy consumption for the AD scenario. However, the global warming potential of the AD scenario was almost half that of the other scenarios.

AD performs very favorably on a system-wide level when environmental burden and reduction in energy consumption are the primary considerations. A thorough environmental impact assessment of a MSW treatment configuration that incorporates AD must take into account the emissions during post-digestion treatment, the need for additional transportation, material handling and processing equipment, and the need for further treatment of any wastewater produced.

Economics

When considering AD of MSW as a waste treatment option, one of the primary concerns of investors, waste treatment managers, and the public is the technology's economic feasibility.

Although any individual anaerobic digester must be considered based on its own merit, which may be quite different from other AD projects, a literature review was conducted to provide a starting point for discussing AD and what has made it feasible where projects have been undertaken.

Several difficulties severely constrain the discussion of the cost of AD:

1. Lack of real cost information

The capital, operating costs, and revenues for most AD projects have not been made public. Furthermore, because of the relatively young age of the technology, many AD systems have been built in stages and re-designed along the way so that the overall cost may not reflect the cost of installing a tried and tested system. Costs may be expected to decline as technologies mature. Also, many of the analyzed systems were built and operated in foreign countries. Labor, land, transportation, taxes, and administrative expenses could affect costs differently than in the U,S. This leads to large uncertainties in the real costs for American OFMSW treatment projects.

2. Dynamic market fluctuations across time and geography

When AD costs are available, converting between currencies is more complicated than simply adjusting prices using the market exchange rate. When comparing gross national products (GDP) of different countries, economists prefer to use purchasing power parity (PPP) over currency exchange rates due to differences in labor, infrastructure, and commodity prices. The PPP adjustment methodology depends on comparing the price of a "basket of goods" selected to represent a broad range of sectors. Using PPP-adjusted dollars instead of exchange rates to report prices of goods and services is a more realistic representation of what the same goods and services would cost in the U.S. While this works well for GDP, it can be problematic for comparing costs of specific industries which may be insulated from certain price differences and more sensitive to others. Furthermore, the PPP adjustment can change over time at a rate different from inflation. Furthermore, different European countries may have different PPP adjustments even if they use a common currency such as the Euro (see Table 9). Also, regional differences within countries can obscure the reliability of cost estimates. Caution must be taken when comparing systems without accounting for regional and temporal PPP differences within and between nations.

Table 9. Purchasing power parity (PPP) adjustment to U.S. dollars for several European countries

Data from the University of Pennsylvania, September 2006.

Country	1995	2000	2003
Austria*	13.48	0.96	0.94
Finland*	6.37	1.11	1.11
France*	6.53	0.97	0.96
Germany*	2.03	1.00	0.97
Greece*	225.81	270.24	0.82
Italy*	1614.43	0.90	0.91
Netherlands*	2.12	1.00	1.04
Spain*	122.00	0.79	0.82
Sweden	9.76	9.90	9.98

Country	1995	2000	2003
Switzerland	2.07	2.01	1.92
United Kingdom	0.64	0.66	0.66
United States	1.00	1.00	1.00
Average Euro	*NA*	*0.96*	*0.95*
* Adopted the Euro as currency by 2003.			

3. Inconsistency in system boundary definition

When comparing AD systems, costs only make sense if the same process steps are included. When interpreting economic studies of AD one must consider which of the following cost items are included in the analysis:

- Predevelopment costs
    - Siting and permitting
    - Land acquisition
    - Environmental impact assessment
    - Engineering planning and design
    - Hydrogeological investigation
- Construction costs
    - Infrastructure (access roads, piping, utility connections)
    - Cleaning and excavation
    - Buildings and construction
    - Equipment (tanks, machinery, electronics)
    - Labor
- Operating costs
    - Maintenance fees
    - Labor
    - Materials
    - Water and energy
    - Supervision and training
    - Insurance
    - Overheads
    - Wastewater disposal
    - Solid residuals disposal
    - Regulatory fees

Digesters can be incorporated into existing waste treatment facilities or they may be operated as stand-alone units. This can affect ongoing expenses as well as the need for capital. For example, material handling equipment, land, and transportation equipment at a landfill could be shared with the digester. A composting operation that installs a digester would not need to build additional aeration beds.

The problems that arise in defining which costs and revenues to include in a financial analysis become especially apparent when comparing AD with other waste treatment technologies. Digesters are commonly compared with landfills, but AD is a waste pre-treatment process, whereas landfilling is a waste disposal option. Only a portion of the typical MSW stream is suitable for AD, and the remaining portion must be disposed of in some other way, such as at a landfill or an incineration facility. A proper economic evaluation of an AD system would assign economic values to the landfill space reduction, energy and other revenues, and environmental protections provided by the system and then compare this against the cost of building and running the system.

In one such study from Australia the environmental benefit associated with AD was given a value of \$4.3/dry MT (\$3.9/dry ton) in 2007 dollars [120]. With the price of electricity at 0.034 \$/kWh, the overall benefits provided by the system only amounted to \$23/dry MT (\$21/dry tons) for a 91,250 wet MT/y (100,600 wet tons/y) AD facility. The amortized capital cost for the system was estimated at \$60/dry MT (\$54/dry tons) while the operating and maintenance costs were estimated at \$69/dry MT (\$63/dry tons).

Clearly, under these assumptions the costs heavily outweighed the benefits. However, the current price of electricity is about twice what it was in 1997 (after adjusting for inflation) and the value of environmental protection is likely to be much higher as well. The study also analyzed a landfill bioreactor installation using the same methodology and found that the costs and benefits were close to equal.

Costs

Despite the difficulties with estimating the cost of operating a digester for conversion of MSW to energy, several studies have attempted to do so and these can provide a starting point for predicting the economic feasibility of an AD of MSW project in the U.S. [23, 107, 120-123]. One comprehensive cost analysis extracted cost data on 16 different MSW AD facilities from the literature and adjusted the data for consistency [121]. The capital costs considered included all predevelopment and construction costs. Operating costs included labor, maintenance, materials, testing, insurance, overheads, and training costs, but not the costs of transporting residuals to disposal sites or any revenues. A second study also published capital and operating costs for a handful of European MSW digesters, but did not adjust the cost data for consistency [120].The capital and operating costs, originally reported in 2003 euros, were converted to 2007 dollars using the average PPP conversion rate for the European countries included in the report (see Table 9). Then the data were multiplied by the consumer price index for 2003 to convert to 2007 dollars[27] and the cost curves were plotted (see Figure 31 and Figure 32).

Although separated by 10 years, the capital cost curves from the two studies were very similar. Differences could be due in part to differences in the cost items included in the different studies. There was an economy of scale of about 0.5 for both studies. The operating cost curves were different for the two studies; however, the earlier data did not fit the curve well, indicating that

[27] A consumer price index inflation calculator can be found online through the U.S. Bureau of Labor Statistics at http://data.bls.gov/cgi-bin/cpicalc.pl, accessed February 2008.

they may not include the same cost items. The data that fit the cost curve had an economy of scale of 0.6.

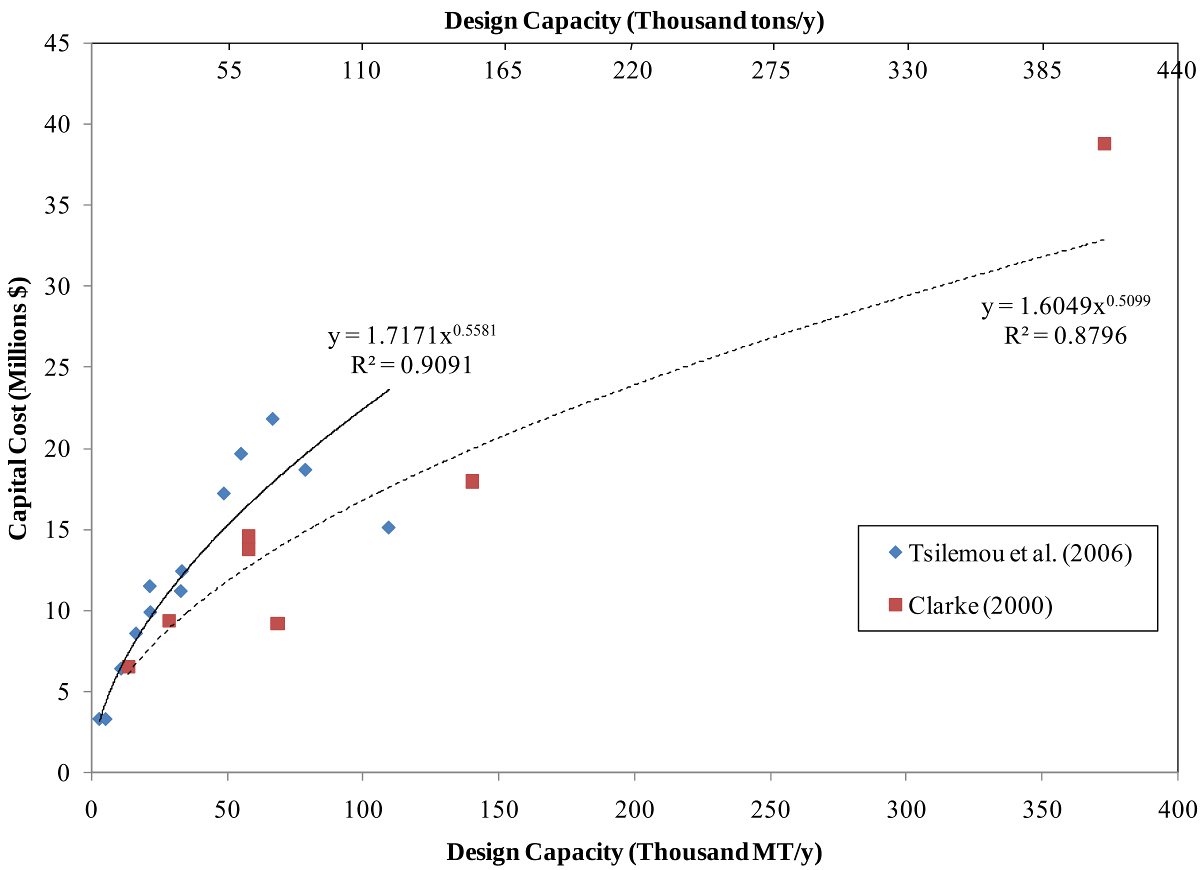

Figure 31. Capital cost curves for European MSW digesters
PPP and inflation-adjusted to 2007 dollars [120, 121].

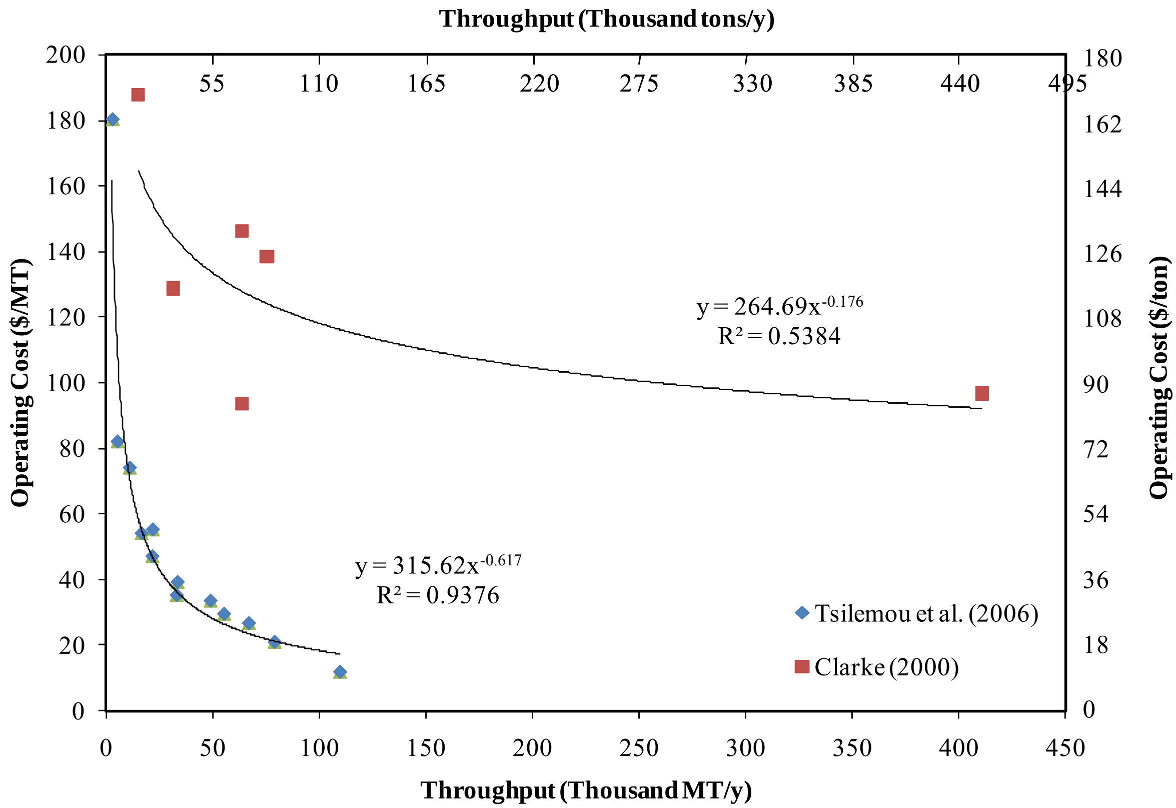

Figure 32. Operating cost curves for European MSW digesters
Inflation-adjusted to 2007 dollars [120, 121].

In a feasibility report for the scale-up of the APS digester system designed by UC Davis researchers, the estimated capital cost for a 70,000 MT/y (76,000 tons/y) digester proposed for the CSU Channel Islands campus was $17 million [50]. According to the above cost curve, the predicted cost for such a plant is about $19 million. A feasibility study for a similarly sized 63,000 MT/y (69,00 tons/y) digester in Iowa estimated the capital and operating costs to be $14.2 million and $11.14 per MT ($10.11 per ton), respectively [104]. The study found the project to be economically marginal and highly dependent on the amount of heat sold.

Although MSW digesters are more expensive than farm and dairy digesters, agricultural waste does not require any sorting equipment or post treatment processing. Most farm digesters either discharge effluent to on-farm manure lagoons or directly land-apply the wastewater. Farm digesters also do not typically receive tipping fees for treating their waste.

Revenues

Revenues for anaerobic digesters can come from any combination of the following sources:

- Energy (gas, heat, electricity)
- Tipping fees (landfill disposal offset)

- Secondary products (compost, water, liquid fertilizer, feedstock for further downstream processes)
- Carbon offset credits
- Government incentives (renewable energy tax credits, price supports)

The weighted average 2007 wholesale price of electricity (through August 24, 2007) for the SP 15, a California trading hub, was $0.067 per kWh, according to the Energy Information Administration.[28] An anaerobic digester sited at waste treatment facility could offset the facility's own electricity demand, in which case the revenue for electricity would be based on the retail price of electricity which may be 25-40 percent higher than wholesale. Many states, including California, now offer net metering which allows distributed energy producers to cover all of their own electricity demand regardless of when it occurs. This effectively gives the electricity produced full retail value, as long as it does not exceed consumption. However, most digesters produce more electricity than they can use; therefore they must either offset another industry's usage or sell the excess electricity. Rural biogas producers throughout the U.S. have had prohibitive difficulty negotiating with utility companies [124]. Without the backing of the federal or state statutes that encourage utilities to negotiate with distributed energy producers, digesters of MSW may not be able to attain the needed electricity revenues.

Natural gas could be an alternative to electricity. Biogas is 55-65 percent methane with the remainder being primarily CO_2, water vapor, and trace amounts of H_2S. If the methane concentration is increased to over 95 percent by removing the CO_2 and trace contaminants, the biogas can substitute for natural gas. The June 2007 City Gate price of natural gas was $0.297 per m^3 ($8.42 per thousand scf) or $0.027 per kWh[29]. Natural gas markets may be more accessible than electricity markets, since purified methane can be compressed for storage, allowing the energy to be supplied as needed. Furthermore, natural gas can be used as a transportation fuel (CNG) which extends the range of uses for the biogas and makes AD projects eligible for higher tax credits in the U.S.

Several tax credits are currently available for renewable energy producers in the U.S. The Energy Policy Act of 1992 (Section 1212.e.2) established a $0.015 per kWh federal tax credit for electricity produced from renewable resources. According to IRS Federal Tax Form 8835, the 2006 inflation adjusted credit came to $0.019 per kWh, but electricity produced from biomass not specifically grown as an energy crop was only allowed to take half of the credit, or $0.0095 per kWh. Furthermore, the eligibility period for landfill gas and agricultural waste projects established after 2005 was 10 years, but projects using cellulosic waste were only eligible to take the tax credit for 5 years. For renewable natural gas, the Nonconventional-Source Fuel Credit

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[28] The EIA posts Intercontinental Exchange data on electricity prices weekly at http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html.

[29] The EIA posts monthly wholesale and retail prices on natural gas at http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/natural_gas.html. The City Gate price is the price at "a point or measuring station at which a distributing gas utility receives gas from a natural gas pipeline company or transmission system." This is presumably the wholesale price a distributed producer might expect if they pipe their gas directly to the municipal system. However, no precedent has been set for this to the author's knowledge and the final negotiated price could be different.

could be claimed at $4.72 per barrel-oil-equivalent[30] for purified biogas injected into the natural gas pipeline, or the Alternative Vehicle Fuel Credit (Internal Revenue Code §§ 34, 6426(d), 6426(e), and 6427(e)) could be claimed at $0.50 per gallon gasoline equivalent[31] for biogas sold as transportation fuel. No eligibility period for these tax credits is expressly stated, but the tax code changes annually and credits are often revised. This uncertainty in the longevity of governmental support for renewable energy may be partly responsible for the reluctance of investors to develop AD facilities for the treatment of MSW in the U.S.

The financial viability of AD projects depends greatly on the size of tipping fees received for treating the waste [50]. The average tipping fee for waste hauled to landfills in the U.S. in 2004 was $37.79 per MT ($34.29 per ton) [125]. Between 1985 and 1998 tipping fees increased at a relatively steady rate of $2 per year, but tipping fees stagnated after 1998. They were also found to vary widely by region [125]. In 2004 tipping fees ranged from $26 per MT ($24 per ton) in the central U.S. to $77 per MT ($70 per ton) in the northeastern U.S. In California, landfills received an average of $34 per MT ($31 per ton) in 2000, which was actually slightly lower than the average 1995 tipping fee, but within California tipping fees ranged from $2.75 per MT ($2.50 per ton) to $94 per MT ($85 per ton) [32]. Because AD facilities only treat OFMSW, the tipping fees charged could be different from those charged by landfills and MRFs. Tipping fees charged by incineration facilities have historically been slightly higher than landfill tipping fees [125]. The price of tipping fees received by AD facilities could be influenced by transportation costs, environmental restrictions and land pressures, as well as competition between facilities accepting OFMSW, especially as the sector expands.

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[30] IRS Tax Form 8907 explicitly sets the conversion rate for barrels-oil-equivalent at 5.8 million BTU per barrel.

[31] Section 11113(b)(2) of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) defines a gasoline gallon equivalent as “the amount of such fuel having a BTU content of 124,800 (higher heating value).”

[32] Tipping fee data for California were reported on the CIWMB web site at http://www.ciwmb.ca.gov/Landfills/TipFees/TFSums.htm, accessed on June 25, 2008.

Conclusions and Recommendations

Anaerobic digestion of OFMSW in Europe has developed primarily due to public policy and demand for reduced landfilling of biodegradable materials. In the ten years since the Landfill Directive, AD technology progressed substantially and trial-and-error allowed companies to refine and standardize their systems. This experience is largely lacking in the U.S. However, several research groups in the U.S. are actively involved in adapting and improving existing MSW AD systems.. Given the large amount of data and business experience available in Europe, development of an OFMSW AD industry in North America should occur faster if favorable policies and market conditions building from those in Europe but specific to US conditions are developed.

The AD of MSW is a rapidly growing field. Debate exists over the future direction of technology development. Interesting new digester designs such as sequential and phased batch and two-stage digesters are currently being tested in the lab as well as in the marketplace. AD technologies have the potential to reduce the environmental impact of waste disposal while capturing biogas energy. In addition, AD technologies have been shown to complement other organic waste diversion technologies such as incineration and composting.

Technological Issues

When designing a digester system, planners must consider the specific needs of the site and available waste stream as well as the existing infrastructure. A summary of advantages and disadvantages of the different AD systems is provided in Table 10.

Table 10. Summary of digester technology advantages and disadvantages.

	Criteria	Advantages	Disadvantages
Single-stage, Wet Systems	Technical	Derived from well developed waste-water treatment technology Simplified material handling and mixing	Short-circuiting Sink and float phases Abrasion with sand Complicated pre-treatment
	Biological	Dilution of inhibitors with fresh water	Sensitive to shock as inhibitors spread immediately in reactor VS lost with removal of inert fraction in pre-treatment
	Economic and Environmental	Less expensive material handling equipment	High consumption of water and heat Larger tanks required
Single- stage, Dry Systems	Technical	No moving parts inside reactor Robust (inert material and plastics need not be removed) No short-circuiting	Not appropriate for wet (TS <5%) waste streams
	Biological	Less VS loss in pre-treatment Larger OLR (high biomass) Limited dispersion of transient peak concentrations of inhibitors	Low dilution of inhibitors with fresh water Less contact between microorganisms and substrate (without inoculation loop)
	Economic and Environmental	Cheaper pre-treatment and smaller reactors Very small water usage Smaller heat requirement	Robust and expensive waste handling equipment required
Two -stage Systems	Technical	Operational flexibility	Complex design and material handling
	Biological	Higher loading rate Can tolerate fluctuations in loading rate and feed composition	Can be difficult to achieve true separation of hydrolysis from methanogenesis
	Economic and Environmental	Higher throughput, smaller footprint	Larger capital investment
Batch Systems	Technical	Simplified material handling Reduced pre-sorting and treatment	Compaction prevents percolation and leachate recycling
	Biological	Separation of hydrolysis and methanogenesis Higher rate and extent of digestion than landfill bioreactors	Variable gas production in single-reactor systems
	Economic and Environmental	Low cost Appropriate for landfills	Less complete degradation of organics (leach bed systems)

Material Handling

The most common problems faced by digester operators are mechanical, not biological. Biochemical imbalances may arise when mixers, pumps, and temperature controllers fail, but the problems are mechanical. The importance of well-engineered systems cannot be understated. Using high quality equipment can help prevent failures and reduce power requirements. The design and construction firms also should have experience building such systems. Material-handling equipment for a solid waste digester is very different from that used by wastewater and farm waste digesters. The firms involved should have experience with designing and operating digesters and systems that handle solids.

Source separating the OFMSW alleviates some of the material handling requirements, but even source-separated waste contains contaminants that need to be removed prior to digestion. This has led some waste managers to eliminate source separation efforts in favor of more extensive mechanical sorting at disposal sites and transfer stations. In the U.S., debate continues on the benefits and costs of source separation efforts and the outcome will have a significant impact on AD systems. High-solids digesters are more tolerant of contamination than low-solids systems and therefore more suitable if a change in sorting technique is anticipated.

Operations and Management

Biomass energy technologies require intimate understanding of physical, chemical, and biological processes, making them unique among energy technologies. Current waste management techniques in the U.S. focus more heavily on understanding geologic processes, and even composters may not appreciate the difference between aerobic and anaerobic biological processes. As commercial AD technologies have evolved in Europe, the plant managers were able to simultaneously develop their digester management skills. Although European digester technology can be borrowed and rapidly adapted for use in the U.S., AD management skills are likely to develop more slowly. If the sector develops too quickly, there is a danger that poor management could tarnish the image of AD for MSW treatment. For this reason, new AD projects must emphasize manager training as well as technology development and marketing.

Integration of MSW Digestion

As an alternative to launching full scale AD of MSW in the U.S., planners may wish to consider intermediate technologies that incorporate AD into current waste management practices. It is important to appreciate how a country's socio-economic atmosphere can influence technology choices and realize that what works in Europe and Canada may not work in the U.S. For example, waste disposal garners much higher tipping fees in Europe than in the U.S. and odor control requires stricter management strategies. This may be due to higher population density in Europe which leads to more stringent space restrictions. Technologies which have not appealed to the European AD of MSW sector, such as leach-bed batch digesters and landfill bioreactors, could be seen as more appropriate for the U.S.

Wastewater Treatment

Many wastewater treatment plants in the U.S. already use AD to convert the incoming organic waste and/or wastewater treatment sludge to energy. Although early wastewater treatment developers postulated that someday we may be able to dump our garbage into the sewer [69], such a system has not proved tenable. Nonetheless, the OFMSW is theoretically treatable much in the same way as wastewater. If wastewater digesters are oversized or underutilized, they could theoretically be used to incorporate OFMSW treatment with some changes in the material handling equipment. The East Bay Municipal Utility District in Northern California is currently investigating the incorporation of food waste into its wastewater treatment sludge digesters.

Many of the MSW digesters in Europe co-digest wastewater treatment sludge with OFMSW in digesters designed specifically for treating solid waste. However, in at least one report, low-solids digesters at wastewater treatment facilities have also been used to codigest OFMSW. In Italy, MSW sorting stations were installed at two wastewater treatment plants and the sorted OFMSW was added to the pre-existing digesters [42]. At the Viareggio plant, 2.2 MT/d (2.4 tons/d) of sorted SS-OFMSW was added to a 3,000 m^3 (800,000 gal) mesophilic digester as a pilot experiment. The digester had previously been treating thickened WAS. The additional organic material only increased the OLR by 20 percent (from 1.0 to 1.2 kg $VS/m^3/d$ [0.008 to 0.010 lbs VS/gal/d]) but the biogas production rate increased by 58 percent (from 600 to 950 m^3/d [21,000 to 33,500 scf/d]). The biogas yield from the SS-OFMSW was 0.56 m^3/kg VS (8.97 scf/lb VS), which was twice that of the waste activated sludge. Due to the dramatic results, the plant was planning on increasing the amount of MSW treated to 30-50 MT/d (33-55 tons/d). At the Treviso plant enough OFMSW was added to the sludge digester to make up 40 percent of the VS loaded, which doubled the OLR and augmented the biogas production rate five-fold. An economic analysis was made as well, which revealed that if the additional biogas could be sold, an overall payback period of 3.5 years could be achieved on the plant upgrade. Thus, wastewater treatment facilities may be able to digest a significant amount of OFMSW without the need to build new digesters.

Permitting issues may exist for allowing wastewater facilities to treat solid waste in the U.S., but surmounting these issues may be simpler for a plant already involved in waste treatment as opposed to permitting a new facility. In addition, large wastewater treatment plants could utilize the additional electricity produced. U.S. wastewater treatment facilities should be evaluated to determine how much additional organic load they could support and to calculate the additional waste diversion that could be achieved.

One possible drawback of incorporating OFMSW into a wastewater treatment digester is contamination of the residual solids. Sewage sludge can be contaminated with heavy metals and other hazardous materials and the resulting compost may need to be classified as hazardous waste, whereas source-separated OFMSW (SS-OFMSW) such as kitchen waste could produce clean, usable compost. When land-application of the residual solids is desired, a separate digester would be recommended for treating OFMSW.

Landfill

The U.S. leads the world in landfill gas collection with over 300 biogas-generating landfills, and many plants are now experimenting with alternate landfill configurations that enhance biogas production rates and yields [126]. The gas is typically used for electricity and/or heat production, but a few projects upgrade the gas for use as a feedstock for chemical manufacturing or as pipeline-grade natural gas. However, in a study of 25 California landfills with gas collection, it was estimated that twice as much methane is lost through landfill emissions as is captured as biogas [126]. It may be economically attractive for landfills to install sorting stations for isolating the most biodegradable portion of the MSW stream and digest the OFMSW in a standalone unit. For landfills that already process biogas, installation of AD for energy capture from MSW may not require substantial additional investment, especially if the landfill already sorts the organic fraction. Furthermore, siting AD facilities at landfills reduces the transportation needed for the non-digestible portion of MSW and may not require additional permits.

As an alternative, some landfill cells can be modified to operate as leach-bed batch reactors, which speeds up methane production and allows for higher methane capture rates than simple landfills (see Batch Digesters). This has not been a common practice in Europe primarily because of regulatory restrictions on landfilling of organics. Such restrictions do not exist in the U.S., making it an attractive stepping stone to employment of full-scale AD of MSW, especially if the landfill site also composts organics.

Composting

A few current composting sites in the U.S. sort MSW or accept source-separated waste. This makes them ideal candidates for the first OFMSW digesters. Full-scale AD systems require post-treatment aeration stations, for which the existing composting site could be used without further modification. Furthermore, tunnel composters and biomixers could be operated as pre-treatment sorting stations for AD of MSW simply by altering the retention time of the incoming waste, for example by speeding up the rotating drums. Preliminary data from UC Davis has shown that waste treated in a biomixer at one to three-day retention time produces biogas with consistently high yields (unpublished data). In Europe, biomixers are already being used to sort the incoming mixed MSW at AD facilities.

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