Feedstock

1	Facility collects source-separated organic waste from public sources, such as hospitals and schools, or the commercial sector, such as restaurants, food processors and markets.
2	Inputs are mechanically separated so that glass, metal and plastic are recycled, and organic material is pulped and sent to AD. The remaining fraction is exported.
3	Though paper and yard trimmings would easily degrade in an anaerobic digester, there are better recycling options for these streams. Yard trimmings can either be left on the lawn as mulch, as in the case of grass cuttings, or can be composted.
4	While technically any organic waste can be composted, food is highly degradable and can rot and cause odor and sanitation problems in improperly managed composting sites. For these reasons, only the fraction of the putrescible waste stream that has no post-consumer use should be used for AD. In practice, this includes food waste, wet or soiled paper and the fraction of yard trimmings that are too voluminous for composting.

Feedstock Pretreatment	The most common pretreatment, therefore, is simple and proven: separation followed by shredding. Pretreatment processes summary unique to the AD process:
Mechanical Pretreatment	Reduces the size and solid content of entering waste, increasing the amount of soluble organics. Shredding, pulping, crushing, or otherwise reducing the size of the waste gives bacteria access to a greater surface area, reducing retention time.
Diluting	Diluting the waste with water also allows the bacteria to move more freely inside the digester. Sometimes the recovery of recyclable materials is done simultaneously with preparing the organic suspension.
Jetting	Jetting the waste into a collision plate to rupture bacterial cell membranes, form soluble waste and accelerate the availability of useable substrate. This was found to speed up the process of hydrolysis and reduce solids retention time without major effects on process efficiency and effluent quality.
Chemical & Thermo-chemical Pretreatment	Chemical pretreatment changes the composition of waste by reducing particulate organic matter to soluble form. Chemical pretreatment has been tried in a variety of temperature regions, from 35 to 225°C and over a variety of times, from 15 to 120 minutes. Thermo-chemical pretreatment has been shown to reduce retention time by 5 days, resulting in 5-10 day retention times. Thermal and chemical pretreatments do improve hydrolysis and promote solubilization. The most successful treatments have been those where alkalis, usually ammonia or NaOH, are allowed to react and hydrolyze the solid vegetation for some days at ambient temperatures. Ammonia is used to raise the nitrogen content and decrease the C/N ratio. This type of treatment could be applied to solid feedstocks, such as straw or other plant material.
Ultrasonic Pretreatment	Sludge disintegration is most significant at low frequencies (20-40kHz). Low-frequency ultrasound creates large cavitation bubbles which upon collapse initiate powerful jet streams exerting strong shear forces in the liquid. The decreasing sludge disintegration efficiency observed at higher frequencies was attributed to smaller cavitation bubbles which do not allow the initiation of such strong shear forces. Short sonication times resulted in sludge flock deagglomeration without the

destruction of bacteria cells. Longer sonication brought about the break-up of cell walls, the sludge solids were distintegrated and dissolved organic compounds were released.
The anaerobic digestion of waste activated sludge following ultrasonic pretreatment causing microbial cell lysis was significantly improved.

Technology

1 The choice of the technological process for an AD facility involves considering the following factors: space, safety of digestate, biogas production, ease of operation, infrastructure, waste storage method, material handling system, odor control and water and fuel requirements.

2 For a pioneer project, a primary concern is system stability. A mesophilic single-stage digester offers the most robust system because it establishes an equilibrium that can cope with greater environmental fluctuations than a thermophilic system.

3 Related to this concern is ease of operation and minimization of maintenance. A system without moving parts inside the digester is preferred so that the digester will not need to be disrupted in order to service mixers, etc. Another factor is experience and success by the designing firm.

4 The scarcity of space is a crucial consideration. To minimize the footprint of an AD facility, the size of the digester should be minimized, suggesting a high solids content digester.
This ensures that the entire volume is used for digestion and water is not taking up additional space. As an added advantage, the water requirements for this type of system are minimized.

Anaerobic Digestion (AD)	AD is a series of chemical reactions during which organic material is decomposed through the metabolic pathways of naturally occurring microorganisms in an oxygen-depleted environment. AD can be used to process any carbon-containing material, including food, paper, sewage, yard trimmings and solid waste, with varying degrees of degradation.
Digestate	The digestate leaving the chamber is a thick sludge with a moisture content of about 80%, close to the consistency of a milk shake. To transport this would be uneconomic, and so digestate is normally dewatered. The solid is reduced to a liquid content of about 50% - 70% and the remaining water can be collected. Many AD facilities post-treat the digestate aerobically, in a process known as curing, in order to produce high quality compost. AD does not reduce NPK content, making the digestate more valuable as a fertilizer. The liquid remaining from the dewatering process can be used in three ways. Least advantageously, it can be discharged as sewage to a wastewater treatment plant, as it is too active to be discharged directly to fresh water. It can also be recycled in the process for waste pretreatment or to adjust the moisture content in the digester. Finally, it can be sold as a liquid fertilizer. There should be fewer problems in removing effluents of wastewater digestion from the digester: a U- shape pipe, to retain gas, and gravity flow should suffice.
AD Stages Hydrolysis	The Stage in which complex molecules are broken down to constituent monomers.
Acidogenesis	The Stage in which acids are formed. In this process, acidogenic bacteria turn the products of hydrolysis into simple organic compounds, mostly short chain (volatile) acids, ketones (e.g., ethanol, methanol, glycerol, acetone) and alcohols.
Acetogenesis	The Stage or the production of acetate. Biological oxygen demand (BOD) and chemical oxygen demand (COD) are reduced.
Methanogenesis	The stage in which methane is produced from either acetate or hydrogen. Methanogens are very sensitive to changes and prefer a neutral to slightly alkaline environment. <u>If the pH is allowed to fall below 6, methanogenic bacteria cannot survive.</u>
Biogas Composition	Biogas is an odorless and colorless gas

Methane (CH_4) Carbon Dioxide (CO_2) Hydrogen (H_2) Nitrogen (N_2) Water Vapor (H_2O) Hydrogen Sulfide (H_2S)	%	50 – 70 30 – 40 5 – 10 1 – 2 <0.3 Traces	that burns with clear blue flame. Biogas burns with 60% efficiency in a conventional biogas stove. <u>CH_4 is explosive at 5 – 15%.</u>
Biogas Density CH_4 Density H_2 Density	kg/m³	≈0.80 0.68 0.09	
Biogas Ignition Temperature	°C	650 - 750	
Biogas LHV CH_4 LHV H_2 LHV	MJ/Nm³	16 – 22 30.1 10.8	H_2 LHV = 120.1MJ/kg CH_4 LHV=30.1MJ/kg
Average Biogas Production from Town Waste	Nm³/tone	80 -150	100 – 250 kWh / tone (el.power) EXAMPLE ➢ 100 m³ Biogas ➢ 60% CH4 ➢ 420 - 560 kWh (22'350 kJ/m³) ➢ 42 - 56.0 kWh lost ➢ 250 - 336 kWh Thermal ➢ 170 - 224 kWh Electric ➢ 243 kWh Waste Heat ➢ 93 kWh Heat to Plant ➢ 59 kWh Electric to Plant ➢ 165 kWh Electric for Sale The CH_4 content of biogas ranges from 50% to as high as 75%, though most plants report values close to 60%. The remainder of the gas is predominately CO_2, with trace elements of other gases, such as H_2, H_2S (hydrogen sulfide), N_2 and water vapor.
Optimum C/N Ratio	-	20-30	If the C/N ratio is very high, N_2 will be consumed rapidly by methanogens for meeting their protein requirements and will no longer react on the left over C content of the material. <u>As a result, gas production will be low</u>. If the C/N ratio is very low, N_2 will be liberated and accumulated in the form of ammonia (NH_4). NH_4 will increase the pH value of the content in the digester. A pH higher than 8.5 will start showing toxic effect on methanogen population. Proteins (meat), manure high in N. Paper high in C.
Optimum pH-Value of Input Mixture to Digester Acceptable pH-Values	-	6.8 – 7.4 5.5 – 8.5	The pH in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This inhibits or even stops the digestion

			or fermentation process. Methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.5. Later, as the digestion process continues, concentration of NH_4 increases due to digestion of N_2 which can increase the pH value to above 8. When the CH_4 production level is stabilized, the pH range remains buffered between 7.2 to 8.2.
Volatile Solids (VS)			VS → a measure of the weight of organic solids that is combustable "volatilized" at a temperature about 538°C. The biogas production potential of different organic materials can also be calculated on the basis of their volatile solid content. The higher the volatile solid content in a unit volume of Input Material, the higher the CH_4 production. About 50-70% VS can be converted.
Total Solids (TS)	%		TS → The weight of the dry matter of a sample of digested material and reported as a percent of the total weight of the digested material sample. The type of digester used is based primarily on total solids content of the waste.
BOD Biological Oxygen Demand Clean Water Treated Domestic Sewage Raw Sewage Vegetable Washings Cattle Slurry Pig Slurry Silage Effluent Milk	mgO_2 / $L_{POLUTANT}$	 <2 20 - 60 300 - 400 500 – 3000 10000-20000 20000-30000 80000 140000	Microorganisms such as bacteria are responsible for decomposing organic waste. When organic matter such as dead plants, leaves, grass, clippings, manure, sewage, or even food waste is present in a water supply, the bacteria will begin the process of breaking down this waste. When this happens, much of the available dissolved oxygen is consumed by aerobic bacteria, robbing other aquatic organisms of the oxygen they need to live. Biological Oxygen Demand (BOD) is a measure of the oxygen used by microorganisms to decompose this waste BOD, the amount of oxygen required by aerobic microorganisms to decompose the organic matter in a sample of water, such as that polluted by sewage. It is used as a measure of the degree of water pollution. The first step in measureing BOD is to obtain equal volumes of water from the area to be tested and dilute each specimen with a known volume of

			distilled water which has been thoroughly shaken to insure oxygen saturation. After this, an oxygen meter is used to determine the concentration of oxygen within one of the vials. The remaining vial is than sealed and placed in darkness and tested five days later. BOD is then determined by subtracting the second meter reading from the first.
COD Chemical Oxygen Demand	mg / L		The COD test will give a good estimate of the first stage oxygen demand for most wastewaters. An advantage of the COD test over the biochemical oxygen demand (BOD) test is 2 to 3 hours versus 5 days. The COD test also is used to measure the strength of wastes that are too toxic for the BOD test. The quantity of oxygen used in biological and non-biological oxidation of materials in water; a measure of water quality. The COD test predicts the oxygen requirement of the effluent and is used for the monitoring and control of discharges, and for assessing treatment plant performance. The contamination level is determined by measuring the equivalent amount of oxygen required to oxidize organic matter in the sample. <u>COD differs from BOD in that it measures the oxygen demand to digest all organic content, not just that portion which could be consumed by biological processes</u>.
COD / BOD Ratio Potable Water Sewage Wastes Industrial Type Wastes	%	 0.5 – 2 2 – 4 4 - 6	The COD to BOD ratio is nothing more than the COD concentration divided by the BOD concentration for the same sample. In some industrial effluents, BODs *can* be higher than CODs (for example, some effluents which are high in sugars , as can be found in the bakery industry, or soda bottling. Some industrial effluents will have higher demand because of the higher quantities of chemicals that demand oxygen.
AD System Classifications	Design considerations for such facilities are capacity, vertical or horizontal orientation, batch or continuous flow total solids content, number of stages, mixing and pretreatment.		
Capacity Typical Plant Size	ton /year	 50'000-	The Friesland plant in the Netherlands, for example, has a capacity of 230,000

	100'000	metric tons per year. For MSW management systems in the developed world, the smallest digester that is economic is about 50,000 tons per year. Many plants under construction are close to 100,000 tons per year. The size of individual chambers ranges from 70 m3 to 5000 m3. Larger capacities are normally accommodated by the use of multiple chambers because incomplete mixing occurs when an individual chamber gets too large.
Orientation	The selection of a horizontally or vertically oriented tank depends on how material is intended to flow through the system.	
Horizontal	Horizontal tanks minimize the area over which the substrate can settle, but require greater space. It may take less input to mix a horizontal tank because the direction of settling is perpendicular to the direction of propagation.	
Vertical	Vertical tanks are predominately gravity driven forcing the material to flow generally downward, though the exact path can very depending on interior boundaries in the chamber. In some cases, material is pumped into the bottom of the tank and removed from the top, causing general upward flow that is further mixed by a lesser, downward, gravity driven flow.	
AD Process Technology	Two general models are used: the batch process and the continuous process.	
Batch Process Fixed Dome Floating Dome	The substrate is put in the reactor at the beginning of the degradation period and sealed for the complete retention time, after which it is opened and the effluent removed. Usually batch reactors are cylindrical, but on farms, where land is readily available, digestion can also occur in large covered lagoons. The sludge in a batch reactor is normally not mixed, allowing the content of the digester to stratify into layers of gas, scum, supernatant, an active layer, and stabilized solids at the bottom. Influent and effluent valves reside in the supernatent layer and solids must be removed near the bottom. Retention times range from 30-60 days with an organic loading rate between 0.48 and 1.6 kg TVS/m3 reactor volume/day. The disadvantage of this type of system is the large tank volume required due to the long retention time, the low organic loading rate and the formation of a scum layer. Only about 1/3 of the tank volume is used for active digestion, making this a poor option in crowded urban settings.	
Continuous Process	In a continuous process, fresh substrate is added and an equal amount of effluent is removed in an ongoing process. With consistent feedstock input, all reactions occur at a fairly steady rate resulting in approximately constant biogas production. Because there is constant movement, however, material inside the tank is mixed and does not become stratified. This allows for more optimal use of the tank volume. The disadvantage of the continuous process is the removed effluent is a combination of completely digested and partially digested material. To minimize the removal of partially digested material, some designs dictate	

	the path of the digestate inside the chamber, for example through the use of interior walls. The reported residence time for a continuous process is an average across the substrate.		
Plug-Flow & Sequencing-Batch Process	Mixed forms of above described systems have been developed including the plug-flow reactor and the sequencing batch-reactor, which try to combine the advantages of the two extremes. In Sequencing-Batch Reactor the waste is pumped into the reactor once each day. A typical plug flow reactor consists of a trench lined with either concrete or an impermeable membrane. To ensure true plug flow conditions, the length has to be considerably greater than the width and depth. The inlet and outlet to the reactor are at opposite ends, and feeding is carried out "semi-continuously, with the feed displacing an equal amount of effluent at the other end.		
UASB Process (Up-flow Anaerobic Sludge Bed) Developed by Friedman in 1980.	The most widely studied reactor configuration for domestic wastewater treatment. This system uses granular particles containing bacteria that are mixed by the circulating gas. Rotating biological reactors allow wastewater to pass horizontally through baffles that move up and down, impeding movement of bacteria out of the digester. Its primary use is for the treatment of higher strength industrial wastewaters, but it can be used for lower strength municipal wastewater - especially in tropical areas. High organic loading rates, suitable for tropical climate. The lower upward liquid velocities in the UASB reactors resulted in better entrapment of the non-soluble pollutants. Thus it is possible to improve UASB performance by increasing the contact between the wastewater and the organisms. Because of these temperature effects, the UASB process has been more frequently applied to tropical areas where wastewater temperatures are usually at least 20°C.		
EGSB Process (Expanded Granular Sludge Bed)	Better contact of organisms and wastewater can be achieved by ➢ Greater height/diameter ratio, and ➢ recirculation of the effluent, which results in an EGSB. More attractive for treating cold and low strength wastewaters, after primary settling.		
Dry Digestion	%	25 - 30	A higher TS contents leads to smaller and thus less costly, reactors. This ensures that the entire volume is used for digestion and water is not taking up additional space. As an added advantage, the water requirements for this type of system are minimized. This price savings may be offset, however, by the more expensive pumps needed to move denser material. Higher TS values cause excessive resistance to flow in pipes as well. Furthermore, the higher solid content puts more wear and tear on the machinery, requiring more maintenance.
Wet Digestion	%	<15	Systems with lower TS tend to have much better mixing, thus increasing the

			degree of digestion. It also is more ammenable to co-digestion with more dilute feedstocks, such as sewage sludge or manure. On the other hand, they require a larger reactor and higher energy input because there is more substrate to be heated. For many waste streams, large amounts of water must be added to reduce the solids content, thereby adding to cost of either purchasing water or dewatering the sludge to reuse process water. Additionally, lower TS values tend to have heavy particles, such as sand and glass, settle to the bottom.
Hydraulic Retention Time (HRT)	Days	14 -30 (dry) >3 (wet)	HRT → the amount of time the digested material spends in the digester. Reported as the ratio of digester volume to the amount of digested material added per day. HRT affects the amount of CH_4 produced. 1 m^3 / day to $m^3$10 tank has 10 days HRT.
Loading Rate (LR)	VS/day/ m^3	1.6 – 8**	Amount of VS per unit of time per volume of digester. (**30 days HRT)
Optimum Temperature Psychrophilic Mesophilic Thermophilic	°C	30 - 35 <25 25 – 40 50 – 65	The methanogens are inactive in extreme high and low temperatures. When the ambient temperature goes down to 10°C, gas production virtually stops. Satisfactory gas production takes place in the mesophilic range, between 25°C to 40°C. Bacteria operating in Mesophilic range are more robust and can tolerate more environmental changes, incl. temperature.
Average Organic Fraction of MSW (in Industrial Countries) China	% %	20% 6% up to 60	Food and other highly degradable materials Paper Total organic waste

Digestion Technology

Fixed Film Anaerobic Digester	The basic fixed-film digester design consists of a tank filled with plastic media on which a consortia of bacteria attach and grow as a slime layer or biofilm hence the name fixed-film digester. The media is fully submerged and wastewater flow can be in either the upflow or downflow mode. As the wastewater passes through the media-filled reactor, the attached and suspended anaerobic biomass convert both soluble and particulate organic matter in the wastewater to biogas, a mixture of mostly methane and carbon dioxide. Being a completely closed system, however, a fixed- film digester allows more complete anaerobic digestion of the odorous organic intermediates found in stored manure to less offensive compounds.

BTA Process Biotechnische Abfallverwertung GmbH MSW from Households, Agriculture & Commercial Plants	The BTA process begins with mechanical wet pretreatment, where feedstock and recirculated process water are mixed into a pulp in a patented machine known as the hydropulper. For mixed waste, contaminants are separated mechanically using a rake and a heavy fraction trap. The suspension retains the organics, which are pulped into slurry that has a higher concentration of organic material, smaller surfaces and flows easier than the incoming waste, thereby making organics more accessible to microorganisms. The pulp is subsequently pumped into a grit removal system known as a hydrocyclone that removes the finest materials, such as sand, small stones and glass splinters. The result is a clean, thick suspension that can be pumped into the digester. Several different designs for the biological conversion are offered by BTA according to the plant capacity and the use of the biogas and compost. One option for small, decentralized units is a one-stage reactor that ferments the pulp in one mixed fermentation reactor. For plants with a capacity of more than 50,000 tons per year, the multi-stage digester was developed, separating the pulp in a solid mass and a liquid phase by using a dewatering aggregate. The dewatered solid is mixed with fresh water to increase the moisture content and fed into a hydrolysis reactor for 4 days. After hydrolysis, the solid is dewatered again, and the liquid is pumped into the methane reactor along with liquid from the original dewatering. The retention time in the methane reactor is 2 days. The same process can also be carried out without the solid/liquid separation in a two stage facility for medium capacity plants. The biogas produced at BTA plants is 60 - 65% methane and the water needs are met entirely by recirculating process water. The solid digestate is aerobically cured for 1-3 weeks
Valorga Process Valorga International SAS (Montpelier France) Household, Source Separated Organic (SSO) & Gray Waste (non-hazardous/non-recyclable household waste.).	The pretreatment in the Valorga process uses an automatic separator to divide the waste into the organic fraction, including fermentable material, paper and cardboard, and non-organics. The waste is mixed into a thick sludge, with a TS content of 20-35%, and introduced at the bottom of the reactor, which can be thermophilic or mesophilic. The single stage reactor is a vertical, plug-flow cylinder with an inner wall that forces material to go up and around it before being extracted from the bottom. This geometry guarantees that waste has a residence time of 3 weeks in the fermentation chamber, ensuring complete hygenization. Mixing in the digester is done without mechanical mixing equipment through a pneumatic pump that injects biogas into the base of the reactor. The digestate is dewatered through gravity extraction and pressing. Part of the extracted liquid is used to dilute incoming waste and the rest is discharged in sewage. The solid cake, with a TS content of about 40%, is treated aerobically for about two weeks to completely stabilize it. Inert material is separated from the compost through a rotary screen. A biofilter treats the gases produced to eliminate odor. It should be noted that the Valorga process is ill suited for low solid concentration "wet digestion," as sedimentation of heavy particles inside the reactor will occur at a TS content less than 20%
Linde KCA/BRV Process Linde-KCA Dresden HmbH Linde has headquarters in Germany,	Linde offers two types of digestion, wet and dry. The Linde wet digestion systems are either one or two stages and can be mesophilic or thermophilic. These plants include pulping waste with water and contaminant removal

Austria and Switzerland	using a drum screen. The defining characteristic of the Linde system is the gas recirculation in the digester using a centrally located drought tube that also supplies heat. Many wet digestion plants employ codigestion with sewage sludge or manure. Upstream of the digester, the feedstock is treated aerobically allowing hydrolysis and acid formation to occur. The dry digestion process, for 15-45% TS, uses horizontal plug flow reactors of a rectangular cross-section. The dry digestion is particularly suited for mixed MSW and yields biogas at a rate of 100 m3/metric ton of feedstock. The digested solid material is dewatered in a centrifuge and treated aerobically by means of the aerated pile process, tunnel composting or the intensive composting module.
Dranco Process Organic Waste Systems of Belgium developed an AD demonstration plant in 1984 in Gent, Belgium. The first full scale commercial plant employing the patented DRANCO process was in Brecht, Belgium with an annual capacity of 20,000 metric tons.	Today plants employ the DRANCO process as part of the SORDISEP process (SORting, DIgestion and SEParation) of municipal and industrial waste for a maximum recovery of recyclables and energy. In the dry sorting step, Refuse Derived Fuel (RDF), ferrous and non-ferrous metals are recovered. The remaining feedstock is mixed with digested material, usually at a ratio of 1 part fresh waste to 6 parts digested, to form a mix of 15- 40% TS content. DRANCO digestion is a single stage, vertical gravity driven plug flow system, where the waste is introduced at the top of the chamber and removed at the bottom with no other means of mixing. The system is run at low pressures and thermophilic temperatures with a 15-30 day retention time. Biogas production ranges from 100 to 200 m3/ton of waste. The final step is wet separation, in which sand, fibres and inerts are recovered. The solid digestate is dewatered to about 50% and then processed aerobically for two weeks to stabilize and sanitize the material. The biogas can be stored temporarily and purified before being sold
Kompogas Kompogas AG, Switzerland Most of the feedstock for Kompogas plants comes from municipalities that support source-separated collection.	The feedstock is first mechanically treated to remove ferrous materials and then sent through a size-reduction process. Material is also separated to undergo thermal treatment or biological treatment. The organic portion is placed in intermediate storage to ensure a constant flow into the feeder, which produces a homogenous mixture able to be pumped. After passing through a heat exchanger, it is sent to the digestion chamber, a thermophilic single-stage, horizontal plug-flow reactor, for 15-20 days. Undesirable germs and weed seeds are eliminated in this process. Slowly rotating intermittent propellers help to push the waste through the digester, to homogenize and degas the pulp and to keep heavier particles in suspension. The system must be carefully monitored to maintain the solid content between 23 and 28% so that flow can continue unimpeded and heavy particles remain in suspension. Due to the mechanical requirements of the system, the size of the reactors is limited. Added capacity at one site is satisfied by installing additional reactors in parallel. This modular design reduces capital construction costs as well as allowing for a wide range of facility sizes, from 5,000 to 100,000 metric tons per year. The digestate is separated into liquid fertilizer and solid compost, both of which are marketed. The solid undergoes additional aerobic curing for three to four weeks in an enclosed facility. For the materials to be sent to landfill, the solid undergoes a total of six weeks of anaerobic stabilization.
WASSA Process	Metals are removed first and the feedstock is then mixed with process water

Citec Finland & Sweden The process offers waste management options for MSW, slaughterhouse waste, fish waste, industrial liquid waste and co-digestion of sewage and household waste.	for wet separation. Digestion occurs in a vertical digester and is carried out at either mesophilic or thermophilic temperatures with TS content of 10-15%. The digester consists of a single vessel that is subdivided internally to create two separate chambers, dividing the single stage reactor into two stages. Mixing is attained through injection of biogas at the base of the reactor and through top mixing when digesting household waste. The digestate is dewatered and can be aerobically composted, depending on the type of waste. The WASSA process achieves 60% volume reduction and 50-60% weight reduction.
Maltin Process Organic Power Ltd is a British company formed in 1997 to develop and license the patented Maltin® System, which it developed from the concepts of Christopher Maltin and his team at Maltin Pollution Control Systems (1967) Ltd.	The Maltin System changed the shape of a digester to ensure more complete mixing. The Maltin System suggests that the digestion process can be improved by changing the shape of the digester to a minimal energy curve produced by folding one end of a rectangular metal sheet onto itself, as seen in Figure. Material enters from one lobe, for example the left, and is removed downstream from the opposite lobe, the right in this case. Additionally, biogas is bubbled through the tank, up from the center cusp, forming a barrier across which the undigested material can not cross. This set-up dictates the flow pattern inside the tank and guarantees that the sludge will undergo a full circuit before being allowed to transfer into the next tank. Additionally, the Maltin system uses eight consecutive tanks, further ensuring that the material will be fully digested as it leaves the final tank. As with other multiple stage digesters, the conditions of each tank are optimized for the processes occurring inside. The Maltin system controls the flow of the material, the length of time it remains inside the digesters and therefore the degree of digestion. Though this system maintains a 15 day retention time, the final organic loads are far lower than traditional tanks, suggesting that the retention time could be cut by using fewer tanks.
HIMET Process Gas Technologies, Inc. has developed a multiple stage process to minimize retention time and maximize the production and concentration of methane in biogas. Their systems are called the HIMET Process and the SOLCON design.	The HIMET Process is a two stage reactor that physically separates acidogenic and methanogenic bacteria into two smaller tanks, maximizing their growth by maintaining optimum conditions in each tank for that particular group of bacteria. The first group is grown in the acid digester where the pH is naturally low and the residence time is maintained between 1-3 days. The methanogens grow in the methane digester where the pH is higher and residence times range from 7-10 days, depending upon the waste characteristics. When feed is transferred from the first to the second digester, the acidogenic bacteria can not thrive as they have already consumed most of the feed material. Alternately, the methanogenic bacteria will die in the acidic first digester. The two-stage process of GTI was a winner of *R&D* magazine's "R&D award for being "one of the 100 most technologically significant products or processes of 1996." The system provides higher efficiencies, a more stable design, a higher throughput, smaller tank sizes by 40-60%, higher methane content in the biogas (65-75% methane vs. 50-55% for conventional technologies), higher pathogen destruction, and lower volatile solids in the digested solids, thus producing much lower odor and more stable soil conditioners
Arrow Bio Process The ArrowBio process, developed by	The ArrowBio process receives unsorted MSW and unloads it into a large water vat where recyclables are separated by density – glass and metal sink

Arrow Ecology, is new to the field of AD with only one operational plant. The methods have undergone laboratory and field testing over the past five years at the plant near Hadera, Israel and are being marketed now under the ArrowBio process in Israel, the United States and Europe.
The first plant opened in 2002 near Kfar Saba, Isreal, treating 200 tons per day, and has the 20 year contract for the town's MSW.

to the bottom while plastic floats.
The organic fraction remains in solution or fine suspension and is sent to a hydrocrusher and then two sequential upflow anaerobic sludge blanket (UASB) reactors.
Waste enters the reactors from the bottom and gas and effluent are removed from the top, resulting in layers of sludge.
The chamber is maintained at atmospheric pressure and room temperature, about 35°C.
The digestate is dewatered and the company claims that the solid is immediately available to be sold as fertilizer.
The plant is module so that it can be scalable from 100-1,000 tons per day.

Modern AD Designs

Traditional Digester

In a traditional digester, the only substance inside of the chamber is the slurry that is being digested.
When the digester is started, innoculum from a working digester is placed in the chamber in order to establish the bacteria population.
From that point forward, feedstock is added appropriately and effluent is removed. In continuous flow digesters, great numbers of bacteria are washed out with the effluent because they are attached to the solids that they are digesting. In digesters on dairy farms, for example, new bacteria populations arrive with incoming manure and leave with exiting effluent.
Equilibrium may still be reached, however, because there is very little change in feedstock, ensuring that the same kinds of bacteria are entering and leaving. With variable waste, however, washing out bacteria will alter interior conditions.

Anaerobic Attached Film Expanded Bed (AAFEB) reactor

In 1980 designed by Switzenbaum and Jewell.

In this process, waste flows upward through bacteria attached to a bed of suspended media.
Expanded Bed reactors use sand or granular activated carbon as a substrate on which bacteria can live.

Up-flow Anaerobic Sludge Blanket (UASB) reactor.

Description see above under Process.

Fixed-Film Digester (FFD)

Designed by researchers at the University of Florida.

The design is similar to traditional digesters, with the addition of the film.
It consists of fixed roof digester tank and pumps for influent, recycling, and effluent.
Inside the digester, vertically arranged corrugated polyethylene drainage pipes are installed in four zones as the media on which the bacteria will live.
This widely available material is an inexpensive solution to providing sufficient surface area in the digester for microbial attachment on which a consortia of bacteria attach and grow as a biofilm.
Immobilizing the bacteria as a biofilm prevents washout of slower growing cells and provides biomass retention independent of residence time, increasing biomass development.
The greater number of bacteria per reactor volume means less time is needed, and retention time ranges from 2-6 days.
This process is ideal for large volumes of dilute, low-strength wastewater (<1%solids), such as those generated from dairy farms.
Also, fixed film digesters have a smaller footprint, which is important where space is an issue.
They also are able to accomplish much faster start-up than suspended growth systems because of a higher organic loading rate (OLR) and colonization of attached growth systems.
They are more successful because of the inherent preference for bacterial species to live in an attached growth mode versus a suspended growth system.

Zeller International Digester	There is continually research being done on engineering better surfaces on which the bacteria can live. Zeller International may attempt to use small spheres, about 5 mm in diameter, made of recycled crushed glass to put in chambers to give the bacteria a home. These spheres may also have embedded enzymes to speed up digestion.
Sludge Granules Digester	Engineering of sludge granules is a new area of research that serves the purpose of expanding and channeling the catabolic capabilities of the sludge and of shortening the length of adaptation period of the microbes. A unique process involving an intermediary stage between the tanks of a two stage process is being tested at the University of Ottawa to process waste with high solid content. In this process, primary digestion of solids occurs for less than twenty days at which point the digestate is subjected to steam pressure disruption and then put into a second chamber for secondary digestion. The intermediary step causes a steam explosion of the internal water in the non-digested fibers, causing fibers to break apart. The disrupted material is then re-inoculated and re-digested in the secondary stage. A benefit to this system is that it can accept mixed or poorly separated waste.

Control Device (Monitoring) in an AD Process

Ideal indicators for process inhibition should be capable of measuring the progress of sludge digestion, and signal impending upsets before they occur.

Common indicators, such as volatile fatty acids, gas composition and pH, are useful for monitoring gradual changes, but do not directly reflect the current metabolic status of the active organisms in the system.

The control of pH is difficult to achieve because of this build-up of volatile fatty acids and, hence, pH control has been only moderately successful.

One of the important ways to control the microbiological process of anaerobic digestion is to control the organic loading to the system.

Measurements of volatile acids in good, continuously operating systems show variable levels of acetic acid (according to specific conditions), but very low concentration of propionic acid.

Anaerobic Digester/Landfill Waste Gas (Methane) Control Equipment:

Condensate & Sediment traps, Manual and Automatic drip traps; Thermal shut off valves; Pressure relief/pressure regulating valves; flame arresters; flame checks; Waste Gas Burners; Low pressure Back Pressure check valves; flame trap assemblies.

Conclusions

1. Aerobic microbial communities have several specific advantages. They have large free energy potentials, enabling a variety of often parallel biochemical mechanisms to be operated. These communities are therefore capable of coping with low substrate levels, variable environmental conditions and multitudes of different chemicals in the influent.

   They have some very useful capabilities such as nitrification, denitrification, phosphate accumulation, ligninase radical oxidation, etc. which make them indispensable in waste treatment.

2. Anaerobic microbial communities are specifically advantageous at high temperatures and high concentrations, of soluble, but particularly of insoluble, organic matter. They also have special physiological traits, such as reductive dechlorination.

3. In the near future, important progress can be expected with regard to the optimal linkage between anaerobic and aerobic processes. Aerobic treatment needs to be specifically focused on the removal of the soluble pollutants.

4. Both in aerobic and anaerobic treatment there is an urgent need for better control and regulation. Particularly on- line monitoring of the biologically removable load (BOD, NOD) and of the possible presence of toxicants is necessary, to improve both types of processes as well as their combined application.

5. It is evident that a long solids residence time (SRT) is necessary for the treatment of sewage by anaerobic processes, because of the low specific growth rates associated with anaerobic bacteria.

6. Fixed-film microbial growth provides intimate contact between the various anaerobic bacteria, thereby providing rates of reaction and degrees of stability which cannot be obtained in suspended growth systems.

7. Up to 1988, either the expanded (or fluidized) bed reactor or the UASB reactor appeared to offer the most desirable configurations for anaerobic sewage treatment.

   Expanded or fluidized beds have the advantage of hydrodynamic control of film thickness and density, factors which allow them to achieve extremely high biomass concentrations; however, they are more mechanically complicated. They can be improved to a certain degree by increasing the recirculation rate (such as the EGSB).

8. Control of film thickness and density is not currently possible in the anaerobic filter. This places a relatively high lower limit on the HRT that can be utilized, and can eventually lead to process failure by plugging. In general, however, there is a need for more information on the influence of various engineering variables on film density and thickness, especially hydrodynamic factors.

9. In general, the UASB reactor did not use primary treatment, while anaerobic expanded or fluidized bed reactors did. The reason for this lies in the mechanisms of particle entrapment and hydrolysis in the two systems.

10. If secondary treatment is required, the prevention of solids inventory and handling problems, due to the build-up of inert solids in a reactor with long SRT and short HRT would dictate the need for primary treatment.

    If secondary treatment is not required, one could use a shorter SRT to achieve the required treatment objectives, and both solids reduction and soluble organics removal could be accomplished in the same reactor.

11. The fate of various wastewater fractions in an anaerobic reactor must be examined, to determine what are the constituents which make up the influent and effluents from these reactors, and whether some pass through untreated.

    Much of the data in the literature shows that removal efficiencies for sewage have little correlation with organic volumetric loading rate, suggesting that certain constituents in sewage have such low degradation rates, anaerobically, that they are only slightly removed, even under the lowest loading conditions.

    If these constituents are aerobically degradable, then the effluent from even a "perfect" anaerobic reactor may require further polishing before discharge to a stream, requiring secondary treatment.

12. Another open question is the impact of temperature on the kinetics of biodegradation of various fractions. At low temperatures there may be some materials whose rate of degradation is so low that appreciable removal could not be achieved even at a very long SRT. If that is the case, then anaerobic sewage treatment may be economically feasible only in warmer climates.

13. A better understanding is also needed of the distinction between the destruction and conversion of organic matter, and the coagulation and removal of particulate organic matter. The use of solids filtration in conjunction with an anaerobic reactor might be a useful combination.

Abbreviations

AD → Anaerobic Digestion
BOD → Biological Oxygen Demand
COD → Chemical Oxygen Demand
C/N → Carbon (total organic) to Nitrogen ratio
CSTR → Continuous (or Completely) -Stirred Tank Reactor
DEP → Department of Environmental Protection
DOE → Department of Energy
EPA → Environmental Protection Agency (US)
GHG → Greenhouse Gas
HRT → Hydraulic Retention Time
HSB → Hydrogen Scavenging Bacteria
MSW → Municipal Solid Waste
OFMSW → Organic Fraction of Municipal Solid Waste
SRT → Solid Retention Time
TS → Total Solids
TTS → Total Suspended Solids
VS → Volatile Solids