

Review of Current Status of Anaerobic Digestion Technology for Treatment of Municipal Solid Waste

**November 1998
RISE-AT**

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SUMMARY

This report provides a summary of the current status of Anaerobic Digestion Technology for Treatment of Municipal Solid Waste (MSW). A review of systems in operation worldwide has been made, looking at all sizes of systems and types of process design.

The information was collected by RISE-AT in order to understand the current level of anaerobic digestion technology, so that an assessment could be made of the suitability of applying the treatment technology to a small scale, low cost application in Thailand.

The report provides information on the current systems in operation and gives details of example processes, where sufficient information was available. The examples are divided into large scale systems, (with a capacity of 2,000 tonnes/yr or more) and small scale systems, (with a capacity of less than 2,000 tonnes/yr).

From the information collected it is clear that anaerobic digestion systems for digesting MSW are now widely used throughout the world. The majority of plants operate on a large scale, and involve complex plant design. Much of the technology is based in Europe, with Germany and Denmark leading the field in technology and in the number of successful plants in operation.

To increase the rate of digestion and biogas production multi-stage processes are often used. These split the stages of anaerobic digestion, causing them to occur in separate reactors. The environment in each reactor can then be optimised for the particular digestion stage and so increase the reaction rate and amount of gas produced. Other systems use the thermophilic temperature range to increase the gas production rate.

Most of the larger scale, industrial systems process MSW alone, however the simpler, smaller scale systems are more successful when co-digestion with animal manure is used.

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Appendix 1 – IEA BioEnergy Report 1997 – Systems and Market Overview of Anaerobic Digestion

Appendix 2 – General Technical Information on Anaerobic Digestion Technology

1.0 INTRODUCTION

This report summarises the information collected by RISE-AT on the current status of Anaerobic Digestion Technology for Treatment of Municipal Solid Waste (MSW). A review of systems in operation worldwide was made, looking at all sizes of systems and types of process design.

The review was made in order to understand the current level of anaerobic digestion technology worldwide, so that an assessment could be made of the suitability of applying the treatment technology to a small scale, low cost application in Thailand.

RISE-AT has received several requests for information on suitable small scale MSW treatment systems that could be operated at Tambon level, serving communities of around 8,000 people, processing approximately 2 tonnes of organic waste per day. Anaerobic Treatment is one of the technologies being considered to provide a solution to the treatment of organic waste and to produce a useful fuel product (biogas).

2.0 METHODS USED

An investigation was carried out to collect information on the technologies that currently exist to anaerobically treat municipal solid waste throughout the world. All systems were investigated, from large scale industrial systems to small scale processes and current research projects.

2.1 Information Sources

The following sources were used to obtain information for the study:

- RISE-AT library
- RISE-AT contacts directory
- Internet search / web-site links
- Faculty of Environmental Engineering, Chiang Mai University (CMU)
- Biogas Advisory Unit, (CMU)

The contacts and websites that were found to be the most useful for the study are listed in Table 1.

Table 1:- List of Contacts for Information on MSW Treatment

Who	Address	Information Received
Universities/Research Establishments		
University of Wales, Cardiff, Energy Research Group, UK	www.cf.ac.uk/uwcc/engin/research/energy	Received general info on AD from Tony Guarzys
Brunel University, Environmental Engineering, UK	www.brunel.ac.uk/research/environmentnet@brunel.ac.uk gary.taylor@brunel.ac.uk	Received info on AD from Gary Taylor
Tata Energy research institute, India	www.teriin.org rajikv@teri.res.in	Provided information on AD and on research being carried out in India
Appropriate Technology Organisations		
Intermediate Technology Development Group SANDEC - Department for water and sanitation in Developing Countries (Switzerland)	www.oneworld.org/itdg itdg@itdg.org.uk www.eawag.ch/dept/sanzurbrugg@eawagg.ch	Website contains useful info and links Christian Zurbrugg - Programme Officer for Solid Waste Management - provided some useful reference material, but is not aware of any small scale systems in operation.
Other Organisations		
World Resource Foundation	wrf@wrf.org.uk	Useful website and 'Warmer Bulletin' Journal
ERIN	www.erin.gov.au/portfolio/esd/climate/methane	Online handbook - Methane Capture and Use, Waste Management Handbook. Contains some useful info.
International Energy Agency	www.iea.org www.fri.cri.nz/ieabioenergy/home plusk@pipeline.com	Info on IEA AD Tasks IEA Bioenergy Programme, AD Activity Leader - P.Lusk also provided some useful data.
LIOR	www.lior.be info@lior.be	Biogas CD ROM produced by Prof E.J.Nyns & Ir. S. Thomas - which contains a summary of AD of MSW technology.
GREENTIE Greenhouse gas Technology Information Exchange	www.greentie.org	Useful links to bioenergy sites
Centre for Renewable Energy and sustainable Technology	www.solstice.crest.org/common/crestinfo	Searchable database with AD references
Energy Efficiency and Renewable Energy Network	www.eia.doe.gov/cneaf/solar/renewables/renewable.energy.annual/contents.html	Useful Links and Online Renewable Energy Annual 1996
CADDET - Centre for the Analysis and Dissemination of Demonstrated Energy Technologies	www.caddet-re.org nick.hall-stride@aeat.co.uk	Online details of AD systems operating worldwide.

2.0 SUMMARY OF INFORMATION COLLECTED

3.1 Anaerobic Digestion Process – Background Information

Anaerobic digestion occurs naturally wherever high concentrations of wet organic matter accumulate in the absence of dissolved oxygen. Anaerobic microorganisms digest the organic material producing carbon dioxide and methane that can be collected and used as a fuel (biogas). The stabilised solid residue, which averages 40 - 60% by weight of the feedstock, (ref 11), can be used as soil conditioner material. Anaerobic digester systems, (also called fermentation, gasification or methanization), use closed reactors to control the anaerobic process and to collect all of the biogas fuel produced. The yield of biogas depends on the composition of the waste feedstock and the conditions within the reactor. For example, the rate of anaerobic digestion can be increased by operating in certain temperature ranges. The modern anaerobic digestion treatment processes are engineered to control the reaction conditions to optimise digestion rate and fuel production.

A summary of the key parameters that control the digestion process is given in Appendix 2, along with more detailed information on the microbiological steps of anaerobic digestion.

Animal manure has been successfully used as a feedstock for many years, however the organic fraction of msw has a different composition and experience of anaerobic digestion of msw alone, is more recent and less extensive.

The IEA has produced a very useful report that provides information on Anaerobic Digestion for MSW and summarizes current markets and systems. The information is on large-scale systems only. Due to the large amount of applicable information contained in the report, it is included in Appendix 1 in its entirety. (*Appendix 1 – Systems and Market Overview of Anaerobic Digestion 1997*).

3.2 System Classifications

A wide variety of systems have been developed to anaerobically treat MSW. They can be split into a variety of categories such as :-

1) Wet or Dry:

Wet – The msw feedstock is slurried with a large amount of water to provide a dilute feedstock of 10-15% dry solids.

Dry – The feedstock used has a dry solids content of 20 – 40%.

2) Batch or Continuous:

Batch – The reactor vessel is loaded with raw feedstock and inoculated with digestate from another reactor. It is then sealed and left until thorough degradation has occurred. The digester is then emptied and a new batch of organic mixture is added.

Continuous – The reactor vessel is fed continuously with digestate material, fully degraded material is continuously removed from the bottom of the reactor.

3) Single Step/Multi-Step

Single Step – All digestion occurs in one reactor vessel.

Multi-Step – Process consists of several reactors, often the organic acid forming stage of the anaerobic digestion process (acetogenesis) is separated from the methane

forming stage (methanogenesis). This results in increased efficiency as the two microorganisms are separate in terms of nutrient needs, growth capacity and ability to cope with environmental stress. Some multistage systems also use a preliminary aerobic stage to raise the temperature and increase the degradation of the organic material. In other systems the reactors are separated into a mesophilic stage and a thermophilic stage.

4) Co-digestion with animal manure/ Digestion of msw alone

Co-digestion with animal manure – The organic fraction of the msw is mixed with animal manure and the two fractions are co-digested. This improves the carbon/nitrogen ratio and improves gas production.

Digestion of msw alone – The feedstock contains the organic fraction of msw alone, slurried with liquid, no other materials are added.

Based on the information provided in the IEA report in Appendix 1, the current leading industrial concepts are:-

- **Dry Continuous Digestion:** Continuously fed vessel with dry digestate matter content of 20-40%. Minimal water addition makes the overall heat balance very favorable for operation at thermophilic temperatures.
- **Dry Batch Digestion:** Batch system fed with dry digestate matter content 20-40%. During digestion, when the reactor is sealed, leachate collected from the base of the reactor is recirculated to maintain a uniform moisture content and to redistribute soluble substrates and bacteria. A disadvantage of this system is that increased pretreatment is required to provide a suitable refined digestate material.
- **Leach-Bed Process:** Similar to dry Batch digestion, however, leachate from the base of the reactor is exchanged between established and new batches to improve startup, inoculation and removal of volatile acids in the reactor. This is also called Sequential Batch Anaerobic Composting (SEBAC). After a while, when methanogenesis is established, the leachate flow is uncoupled and connected to a new batch.
- **Wet Continuous Single-Step Digestion:** MSW feedstock is slurried with a large amount of water (10% solids). The system leads itself to co-digestion of MSW with more dilute feedstocks such as sewage sludge or animal manure. Effective removal of glass and stones is required to prevent rapid accumulation of these in the bottom of the reactor. The digestate requires pressing to recover liquid, (which can be recycled to mix with incoming waste), to produce a solid digestate for disposal.
- **Wet Continuous Multi-Step Digestion:** MSW feedstock is slurried with water or recycled liquid (10% solids content) and fed to a series of reactors where acetogenesis occurs in a separate reactor to methanogenesis.

3.3 *Examples of Existing Treatment Processes*

Many MSW anaerobic treatment plants are in operation throughout the world. Appendix 1, p16 gives a list of 118 plants either operating or under construction, with a capacity for processing 2500 tonnes/year or more. This list provides full details of where the plants are situated and which company supplied the AD system. Many of the plants are situated in Europe, with the majority of the companies who design and construct the plants being European.

To summarize, the breakdown of facility by country is shown in Table 2 below. It is clear that Germany and Denmark lead the world in the number of plants operating by a significant margin.

Table 2: Breakdown by Country of AD Plants with capacity of 2,500 tonnes/yr or larger

Country	No. of Plants in Operation	No. of Plants under Construction
Austria	10	0
Belgium	1	2
China	0	1
Denmark	21	1
Finland	1	0
France	1	0
Germany	30	9
India	0	4
Italy	4	2
Japan	0	1
Netherlands	4	0
Poland	0	1
Spain	0	1
Sweden	7	2
Switzerland	9	1
Thailand	0	1
UK	0	1
Ukraine	1	0
USA	1	2

Data Source – Appendix 1

There are many companies involved in the design and construction of AD systems for processing MSW. The data in Table 3 shows the companies involved in providing AD systems and the number of plants in operation, or under construction. It also gives the nationality of the company.

(It should be noted that this information is correct as of 1997).

Table 3: Companies supplying AD Plants with capacity of 2,500 tonnes/yr or larger

Company & Nationality	No. of Plants in Operation	No. of Plants under Construction
Arge Biogas, (Austrian)	2	0
Entech, (Austrian)	7	4
Kompogas, (Swiss)	10	0
OWS-Dranco, (Belgian)	4	1
BTA, (German)	11	0
Steinmuller Valorga, Sarl (French)	2	4
Ecotec, (Finish)	1	7
C.G.Jensen, (Danish)	1	0
BWSC, (Danish)	3	0
NNR, (Danish)	6	0
Kruger, (Danish)	12	2
Bioscan, (Danish)	1	1
Prikom/HKV, (Danish)	2	0
Jysk, (Danish)	1	0
CiTEC, (Finish)	1	1
Linde – KCA, (German)	1	0
Schwarting UHDE, (German)	1	0
ANM, (German)	1	0
Haase Energietechnik (German)	1	1
DSD Gas und Tankanlagenbau (German)	2	0
IMK BEG Bioenergie (German)	0	1
Bioplan (Danish)	1	0
TBW (German)	1	0
BRV Technologie Systeme (German)	2	0
D.U.T. (German)	1	0
Paques Solid Waste Systems (Dutch)	3	1
Unisyn Biowaste Technology (USA)	1	0
Duke Engineering (USA)	0	2
WMC Resource Recovery (UK)	0	1
R.O.M. (Swiss)	1	1
Purac (Swedish)	1	0
SWECO/VBB (Swedish)	0	1
NSR (Swedish)	1	0
BKS Nordic (Swedish)	1	0
Projektor (Swedish)	2	0
Biocel/Heidemij Realisatie (Dutch)	1	0
Ionic Italba (Italian)	1	0
Kiklos (Italian)	1	0
SPI (Italian)	1	0
RPA (Italian)	1	0

Data Source – Appendix 1

(The companies highlighted in Table 3 are described in more detail in section 3.3.1).

Examples of some of the major systems in operation are given below. Examples were selected only on the basis that sufficient information was collected during the study to accurately describe the process. Therefore the range of processes described are

intended to give an idea of the range of process designs currently in operation and are not a full review of all possible designs.

3.3.1 Large Scale Industrial Processes (2,000 tonnes/year or more)

i) *EcoTechnology JV Oy System – Finland/Germany (Ref 6)* (Wet Continuous Single Stage System)

EcoTec have had a bio-waste facility operating in Bottrop, Germany since 1995, that processes 6,500 tonnes/yr. EcoTec has several other projects under construction around the world, from a 30,000 tonnes/yr plant in Berlin, Germany, to a 17,000 tonnes/yr plant in Shilou, China. There is also a plan to build a 14,000 tonnes/yr plant in Bangkok.

Source separated waste is delivered to the plant and passes through a primary crushing stage and a magnetic separator before entering a drum screen. Here combustible materials, or Refuse Derived Fuel (RDF), is separated from the waste and is conveyed to a fluidized bed boiler. The remaining organic material is conveyed to the Feed Preparation Tank, where it is mixed with process water to a total solids content of 15%. Solid impurities are removed and the feedstock is then pumped into the anaerobic digestion reactor.

The system operates with two or more parallel process lines. Digestion occurs at 35°C and the retention time of the material is 15 to 20 days. (The process can be applied to operation in the thermophilic range at 55°C.) The size of one reactor can be up to 5000m³. The reactor mass is mixed by a circulating bio-gas system. The digested slurry is pasteurized at 70°C for 30 mins, to make it safe for spreading on agricultural land.

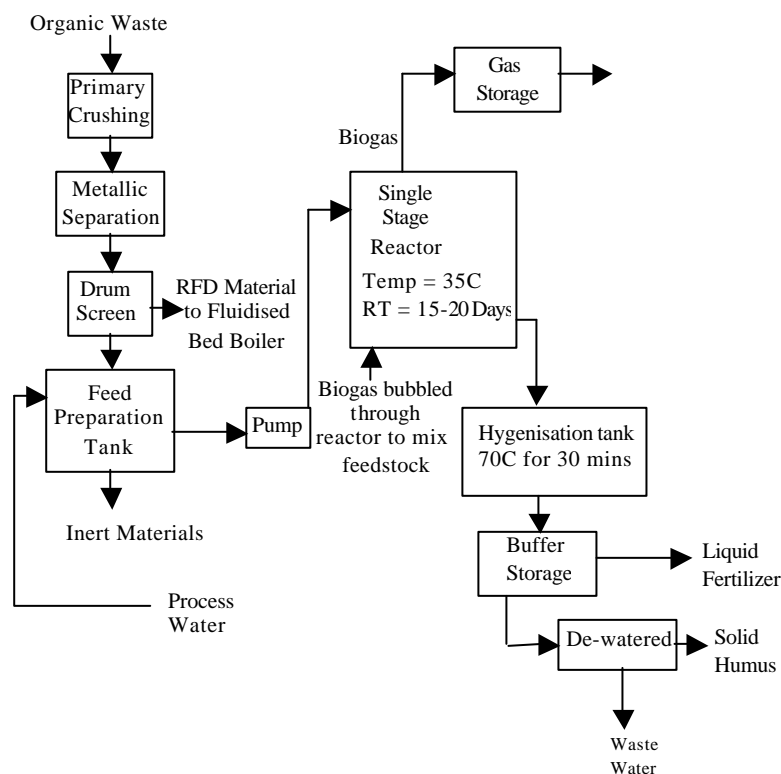


Figure 3.3.1 -1 *Ecotec JV Oy System*

ii) BTA/Carl Bro, Helsingor, Denmark (Ref 7)
(Wet Continuous Multi-Stage System)

The BTA multi-stage plant in Helsingor, Denmark was opened in 1993 and processes only source separated household waste. It has a capacity of 20,000 tonnes/yr. BTA has ten other plants in operation in Austria and Germany, these are all one-stage systems.

At the Helsingor plant, source separated waste is delivered to a pit at the plant. It is transported from the pit to a bag opener and then is conveyed to a hydropulper where the waste is pulped and plastics and inert materials are removed. The pulped biomass is then pre-treated at 70°C for an hour to sanitise it and sodium hydroxide is added to aid the decomposition rate in the following stages. The material is separated into a light liquid and a slurry fraction. The liquid is pumped into the digestion reactor and the slurry goes to hydrolysis tanks, where it is converted into organic acids. The liquid portion from the hydrolysis is then pumped to the digestion tank.

The plant produces approximately 3 million m³ of biogas per year, which is used in a combined heat and power station positioned adjoining the site.

The plant is equipped with a heat exchanger so that heat produced in the digestion process can be used to heat the waste in the pre-treatment stage.

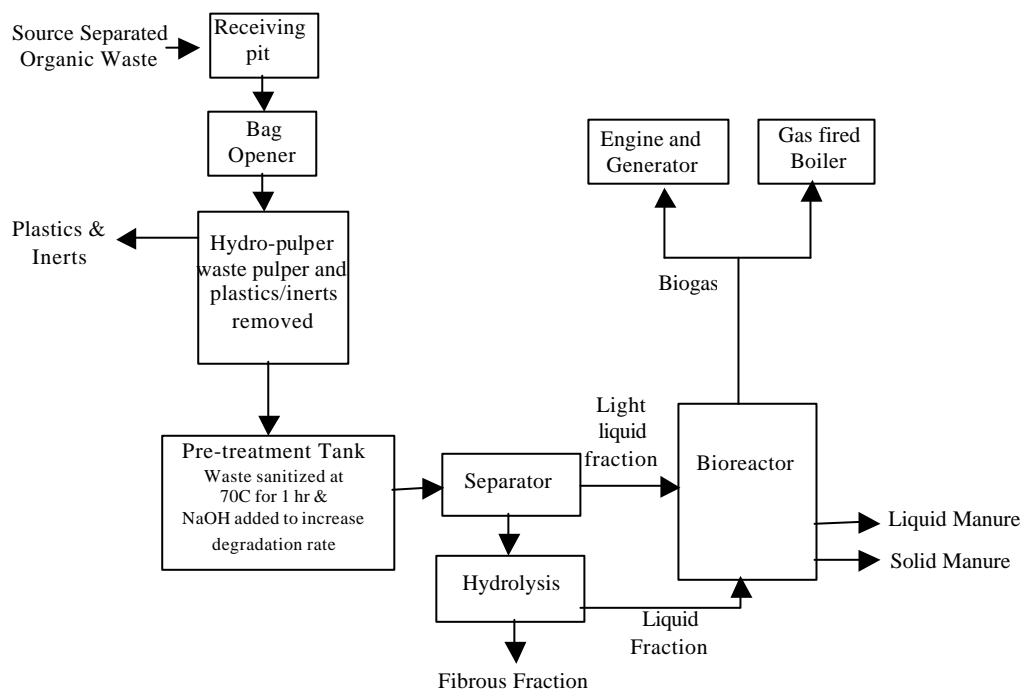


Figure 3.3.1-2 BTA/Carl Bro (Multi-Stage) System

**iii) TBW Biocomp Process, Thronhofen, near Regensburg, Germany
(Wet Continuous Multi-Stage System)**

The plant in Regensburg has been operating since 1996, with a capacity of 13,000 tonnes/yr. Source separated organic waste is processed at the plant.

The Biocomp method uses a combination of compostation and fermentation, (i.e. aerobic and anaerobic decomposition). Source separated organic waste is used with liquid waste from the agro industry. The waste is fed to a rotary screen which acts as a sieve, separating the rough, coarse material from the fine organic fraction. The rough fraction goes to compostation, the finer portion to the anaerobic digestion process. Following separation both fractions are separated by hand to remove foreign, non-organic materials. They are also run through a magnetic separator to remove any iron containing particles. The compost material is conveyed to pits where it is piled up and left for 6 weeks, during which it is turned over once.

The fine organic fraction is fed to a pulper, where it is mixed with liquid separated from the digested sludge, to give a total solids content of 10%. Small, uncompostible objects are removed from the bottom sluice of the pulper, the mixture then passes to a feedtank.

Several times a day batches of material are pumped from the feedtank into the first stage reactor, where a temp. of 35°C is maintained. Propellor type agitation is used. It takes about 2 weeks for the slurry to pass through the first reactor from top to bottom. The active sludge is removed from the bottom drain and fed to the second reactor, entering at the bottom. The second reactor operates in the thermophilic range, a temp of 55°C being maintained. It also takes 2 weeks for the slurry to pass through the reactor, from the bottom to the top. At the end of 2 weeks approx 60% of the original organic content will be converted to biogas. Reactors are equipped with flexible gas collecting membranes at the top, which serve as interim gas storage spaces.

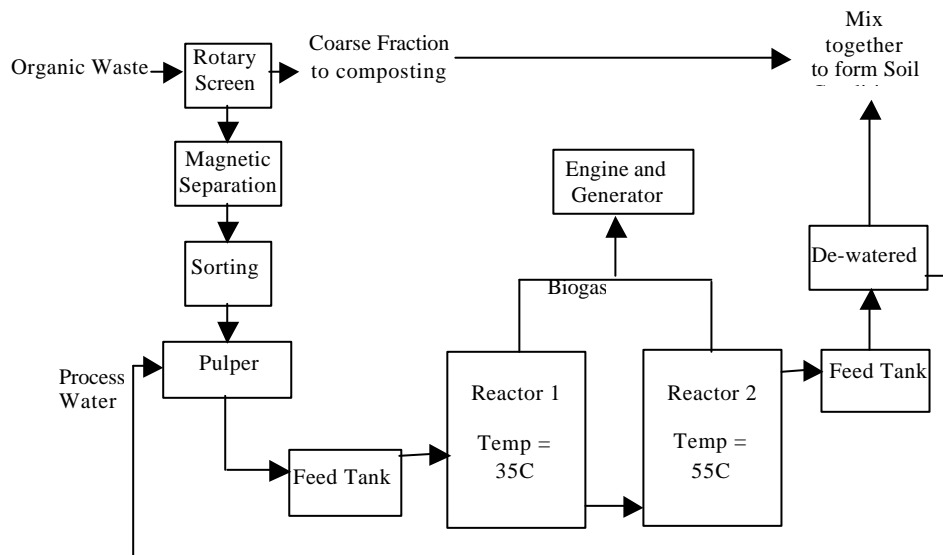


Figure 3.3.1-3 TBW Biocomp Process

The physical separation of the two phases leads to an increase in gas production. 25% of the energy produced from the biogas is used to heat the reactors and the plant buildings.

The digestate is passed to a process where it is press de-watered, the water being re-fed to the input to be mixed with the incoming, fine fraction of organic material. Any surplus water is purified in specially designed purification ponds. The solid part of the sludge is mixed with matured compost to form the final soil conditioning product.

The thermophilic phase of digestion acts as a decontamination process to remove disease causing agents. During aerobic composting, temperatures of 75°C are reached over a period of 4 weeks, this has a similar decontaminating effect.

The digestive environment is closely monitored and highly active digestive slurry is added to the process if modification of the mixture content is required.

Electricity and heat are generated using a water cooled, diesel type aspirating engine, an induction generator and an exhaust heat exchanger. Each m³ of biogas produces 1.5kW_{el} and 3kW_{them}.

**iii) Organic Waste Systems – DRANCO Process, Brecht, Belgium
(Dry Continuous Single Stage System)**

Organic Waste Systems developed the DRANCO process of anaerobic digestion and there are now 4 full scale plants operating in Europe, with capacities from 11,000 to 35,000 tonnes/year. They also have a pilot plant in Ghent, Belgium, treating 700 tonnes/yr. This was built as a technology demonstrator and the process is not economic when operated at such a low capacity.

The plant at Brecht in Northern Belgium has a capacity of 12,000 tonnes/yr and is a dry process.

The process receives source separated organic waste that is manually sorted and shredded, prior to passing through a screen to separate the large particles. A magnetic separator removes metallic particles and the feedstock is then mixed with water, recycled from the process. The feedstock is pumped into the top of the reactor that has a capacity of 808m³.

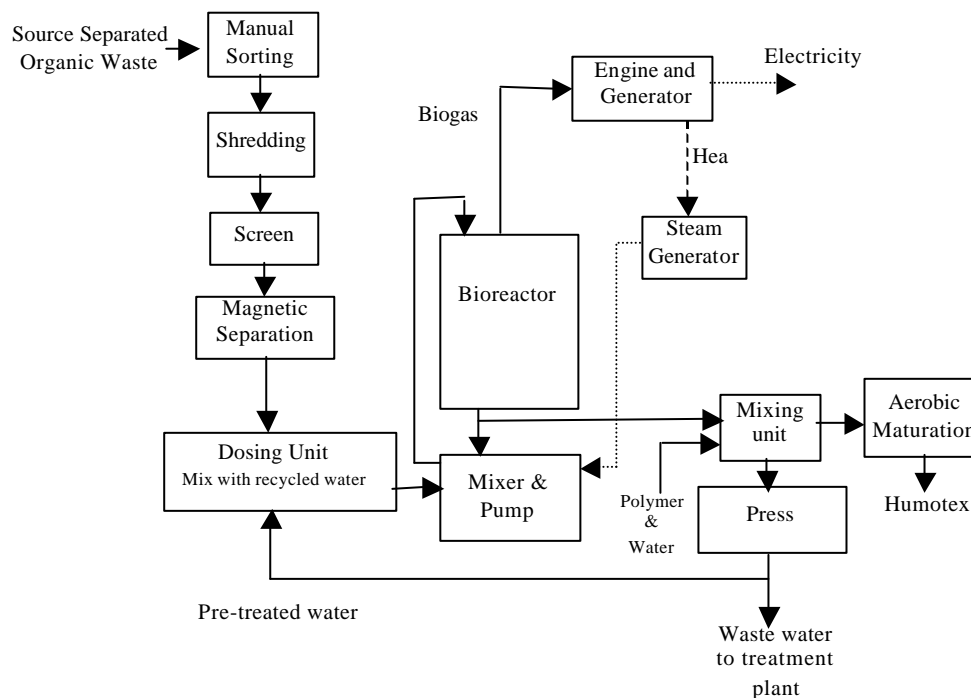


Figure 3.3.1-4 Organic Waste Systems - DRANCO Process

The DRANCO process consists of a single stage, thermophilic reactor (operating between 50 and 58C). The retention time in the reactor is 20 days. 5% of the contents are removed each day and de-watered to 55% solids using a screw press. The filtrate is pre-treated in on-site aeration ponds prior to discharge to the local municipal waste-water treatment plant. The digested residue is extracted from the reactor, de-watered to a TS content of 50%, and then stabilised aerobically for a period of approximately 2 weeks, in a facility with in-floor air ducts. The final product is called Humotex and is a hygienic, stabilised soil conditioning product. About 7% of the gas produced is used to heat the digester.

The total solids content of the feedstock varies between 15-40%, depending on the input material. Organic Waste Systems have also developed a DRANCO-SEP process that operates between 5-20% solids.

3.3.2 Small Scale Processes (less than 2000 tonnes/year)

i) *Indian Vanaspati Kachara Bio-gas Plant (Ref 5)*

The Vanaspati plant uses only organic waste, (household refuse and waste plant material). All materials are cut into small pieces before being added to the digester, which is a simple, single stage vessel, designed for digestion of animal manure. The digester is filled with water and organic waste, a few buckets of spent slurry from an active biogas plant are added at the beginning to speed up the initial process. A continuous system pilot plant was tested and found to be successful in producing gas. However, it was noted that the gas rate varied significantly depending on the type of organic matter added to the digester. At some point, when the gas production dropped significantly, green matter that underwent an aerobic pre-decomposition was added. This increased the gas production back to previous levels. It was also noted that during winter, as the temperature dropped, gas production reduced.

ii) **Garbage Gas Manure Pilot Plant, Agricultural Tools Research Centre, Bardoli, India (Ref 5)**

The plant was a batch type design, which used kitchen waste and general garbage. It included a pre-digestion platform and four digester pits. It was a small scale system with an average retention period of 40 days for each digester. All of the garbage was first shredded into pieces less than 5cm in length. It was then spread under shade on a platform and moistened with water. The waste was turned once a day until the colour changed to brown and it had a spongy consistency, and pH of about 7. It was loaded into pits which were then sealed. A gas tube was connected from the top of the digester to a gas holder floating on fresh water. The tests conducted with different materials concluded that the raw material of a biodigester can fall into 3 categories:

Category	Raw Material	Explanation
Material producing normal, steady biogas yield for a long retention time.	Cow Dung, animal manure	Good C/N ratio, steady rate of gas production
Material yielding profuse gas for a shorter time	Green Succulent material	Initial fermentation stage rapid, acids produced reduce pH level and inhibit further gas production.

Material yielding gas at slow rate for longer retention time.	Municipal Organic Garbage	High carbon, low nitrogen content, therefore nitrogen is used up quickly by bacteria which then react very slowly. Addition of nutrients such as ammonium nitrates and phosphates increase the bacterial growth and so increases gas production.
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Table 4: Results of tests using various raw materials as feedstock

It was found that by insulating the walls of the digester with compost, the temperature increase allowed the process to produce 58% more gas. It was also noted that by mixing material with a C/N ratio of 25-30 with the garbage, the retention time was reduced and the gas production rate improved.

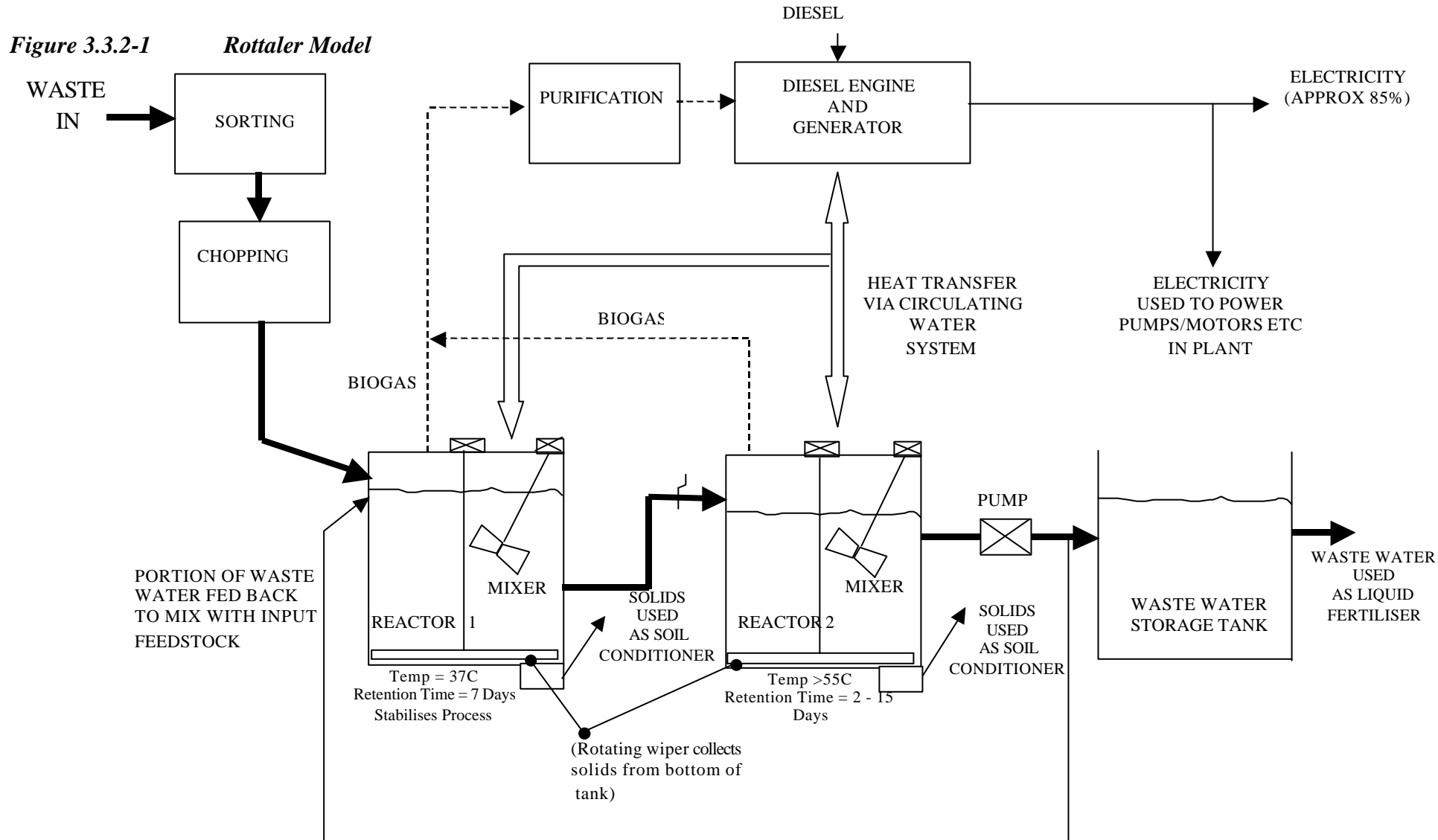
*iii) Rottaler Model, Bavaria, Germany
(Wet Continuous Multi-Stage System)*

The Rottaler Model system was designed to be a low cost, small-scale process, with the emphasis on decentralized plants and a simple process. The plant was developed by Team Agrar Energie in Bavaria, Germany. The current plants process approximately 2000 tonnes/year each, but it is possible to build plants to process from as little as 500 tonnes/year. There are four plants in operation, three use a combination of animal manure mixed with the organic fraction of municipal solid waste, the other operates only on msw, (this plant has been operating successfully for nearly three years). The design of the plant is the same for either process.

All plants have pre-separated organic waste delivered to the plant and use a hand-sorting process to remove items of organic waste that cannot be digested, (primarily wood). The sorted waste is chopped and mixed with recycled process water to a total solids content of 10%, prior to being fed to the first reactor.

The fermentation is split into two phases, the first is a stabilisation process operating at 37°C, with a retention time of 7 days. The digestate is then passed to the second reactor where it is heated to 55°C and maintained for 2-15 days. The solid portion of the digested material falls to the bottom of each reactor tank and is collected by a rotating wiper arm and forced into a collection area. It is pumped out from the bottom of the tanks and used as a soil conditioner. The liquid portion at the top of the tank is removed and stored in a separate tank, from where it is collected to be used as a liquid fertilizer. A portion of the liquid is fed back to the beginning of the process and mixed with the input feedstock.

Biogas is collected from both reactors and purified before being fed to a diesel engine and generator. The electricity produced is used to power the plant, the remainder is fed to the electricity grid system. The heat generated by the diesel engine is used to heat the reactors. A water transfer system is used and the reactor vessels are built with the water pipes embedded in the concrete walls.



ROTTALER MODEL - ANAEROBIC DIGESTION SYSTEM
(System design shown is as understood following initial discussions with suppliers).

*iv) Anyang City, Korea.
(Multi-Stage System)*

The anaerobic digestion facility was developed in Korea due to lack of sufficient space in the highly populated city area for a landfill site. Also, the high moisture and salt content in the food waste hindered any effective composting. The facility in Anyang city processes about 3 tonnes of organic waste per day, (just over 1000 tonnes/year).

Plastic and other non-degradable material is removed by means of a drum screen and an acid reactor. These materials are then sent to a nearby incinerator.

The process consists of two reactors in series, with capacities of 15m³ and 45m³, which separate the acidic and methanogenic phases of the anaerobic digestion process. Effluent from the second reactor is recycled and mixed with the input feedstock.

From the 3 tonnes of food waste processes per day, 230m³ of biogas, 100Kg of humus and 2 tonnes of waste-water are produced.

3.4 Comparison of Different Systems

The following table shows a comparison of the systems described in Section 3.3.

Table 5: Comparison of some existing systems:-

(Gaps indicate that information is not available)

System	Organic material	Pre-Treatment	Process	Post-Treatment	Total Digester Volume m ³	Capacity of Plant tonnes/yr	Date operation started	Remarks
Ecotechnology, Bottrop, Germany	Source Separated household waste only	<ul style="list-style-type: none"> - organic waste separated from combustible materials (RDF). - RDF to fluidised bed boiler 	<ul style="list-style-type: none"> - Single Stage - Temp 35°C - Retention Time 15-20 days 	Slurry to be pasteurised at 70°C for 30 mins	5.0	6,500	1995	
BTA, Helsingor, Denmark	Source Separated household waste only	<ul style="list-style-type: none"> - Pulped - Plastic Removed - Sanitised for 1hr at 70°C - NaOH added. - Material separated into liquid and slurry, slurry hydrolysed 	<ul style="list-style-type: none"> - Multi-Stage - Temp 38°C -Liquid from separation and liquid from hydrolysis digested in reactor. 		2.4	20,000	1993	
TBW Biocomp Process, Thronhofen, Germany	Source separated MSW	<ul style="list-style-type: none"> - Fine organic fraction separated from coarser organic fraction. - Coarser material to aerobic decomp. by composting - Fine fraction pulped and mixed with liquid from digested sludge. - 	<ul style="list-style-type: none"> - 2 stage reactors - Stage 1 – (35°C) Mesophilic - Stage 2 – (55°C) - Thermophilic Retention time is 2 weeks in each reactor 	Solid part of sludge mixed with matured compost.	1000 (for each reactor)	13,000	1996	Separation by hand and mechanical means is used to remove non-organic materials.

System	Organic material	Pre-Treatment	Process	Post-Treatment	Total Digester Volume m ³	Capacity of Plant tonnes/yr	Date operated	Remarks
Organic Waste Systems – DRANCO Process	Source Separated household waste only	<ul style="list-style-type: none"> - Manually sorted - Shredded - Magnetic separator - Mixed with water 	<ul style="list-style-type: none"> - Single Stage - Thermophilic (50 – 58°C) - Retention Time = 15 to 30 days 	Sludge dewatered and stabilised aerobically for 2 weeks.		11,000 to 35,000	1992	
Vanaspati Kachara biogas plant, India	Plant and kitchen waste	<ul style="list-style-type: none"> - waste chopped into small pieces - few buckets of slurry from active system introduced at start up 	<ul style="list-style-type: none"> - Continuous 		8.25	< 200	1989	Aerobic decomposition of green waste used as a pre-treatment to increase gas production
Garbage Gas Manure Pilot Plant, Bardoli, India	Kitchen waste and general solid waste	<ul style="list-style-type: none"> - Shredded - Aerobic pre-digestion 	<ul style="list-style-type: none"> - Batch - Retention Time 40 days 				1989-1991 (approx)	Gas production increased by insulating digester and by mixing waste with manure
Rottaler Model, Bavaria, Germany	Source separated organic waste	<ul style="list-style-type: none"> - hand sorting - chopping 	<ul style="list-style-type: none"> - Multi-Stage - Stage 1 – (37°C)Stabilisation for 7 days - Stage 2 – (55°C)Thermophilic for 2-15 days 	Separation tank, liquid pumped from top, solids from bottom of tank.	540 (each reactor)	2000	1994	Some plants use co-digestion with animal manure
Anyang City, Korea	Food Waste	<ul style="list-style-type: none"> - Sorting - Shredding 	<ul style="list-style-type: none"> - Multi-Stage - Stage 1 – Aetogenesis - Stage 2 – Methanogenesis 		Stage 1 – 15 Stage 2 – 45	1000	1993	

3.5 *Economic Factors*

It is difficult to discuss in detail the economics of implementing an Anaerobic Digestion Plant for MSW, because of the many factors that affect the costs and the variation in circumstances and costs between different countries. For example the following factors will have an influence on the overall treatment costs:-

- Energy Prices
- Energy Taxes & Renewable Energy Policy
- Land Prices
- Labour Costs
- Construction and material costs
- Markets for the compost/soil conditioning product and prices
- Quality of the compost produced

In general, when looking at the treatment cost per tonne of MSW for the large facilities built in Europe, it is clear that over the last few years the trend is for a reduction in overall treatment costs making anaerobic treatment systems more competitive. However, economies of scale mean that the complex industrial systems need to process many thousands of tonnes of MSW per year to have a reasonable treatment cost per tonne.

For example, using the data provided in Appendix 1, 1996 figures show that a plant with a capacity of 100,000 tonnes/yr has a treatment cost of less than 30US\$ per tonne, whereas a plant with a capacity of only 20,000 tonnes/yr has a treatment cost of around 60US\$ per tonne.

Data on smaller scale systems is not available at present. Data has been requested from the Korean facility and is also being collected on the Rottaler model system.

3.6 *Other Information*

Other relevant information collected from a variety of sources is summarized below:-

International Energy Agency (IEA) Bioenergy Programme - Anaerobic Digestion Activity Leader, Philip. D. Lusk:

During correspondence by e-mail with Mr Lusk, he stated that he is not familiar with any small-scale, low cost systems for processing msw. He explained that 'One problem is that most MSW is a 'high solid', with usually between 30-40% total solids concentration. To use conventional digestion systems requires a dilution to less than 15% total solids. There are a few 'high solids' systems being developed that can use undiluted MSW. However, due to the economies of scale issue the pressure is to construct large systems. The market is heading towards 1000 tonnes/day technology to solve the waste disposal pressures of large urban areas.

He suggests that if waste waters from farms or industry are available, it would be best to dilute the feedstock to ~4% TS and use a conventional animal manure biodigester.

SANDEC, Water and Sanitation in Developing Countries - Programme Officer Solid Waste Management, Chris Zurbrugg:

SANDEC has no information on small scale anaerobic systems being used to process msw in developing countries.

Energy Technology Division, Tata Energy Research Institute, India - Research Associate, K.V.Rajeshwari:

Stated that current research work is being carried out to investigate the problems of processing solid wastes in biogas plants designed for cow dung. The main problems being investigated are those related to the formation of scum. The fibrous material present in the solid waste gives rise to scum which floats to the top of the digester and prevents the release of biogas and further digestion of solid waste. A patent has recently been filed for a design for a reactor for vegetable market waste. However, they have not yet reached the stage of commercialisation of the technology and further research is required.

4.0 CONCLUSION

Anaerobic digestion systems for digesting MSW are now widely used throughout the world. The majority of plants are large scale, processing over 2,500 tonnes of waste per day and involve complex plant design. Much of the technology is based in Europe, with Germany and Denmark leading the field in technology and in the number of successful plants in operation.

To increase the rate of digestion and biogas production multi-stage processes are often used. These split the stages of anaerobic digestion, hydrolysis, acetogenesis and methanogenesis, causing them to occur in separate reactors. The environment in each reactor can then be optimised for the particular digestion stage and so increase the reaction rate and amount of gas produced. Other systems use the thermophilic temperature range to increase the gas production rate.

Most of the larger scale, industrial systems process MSW alone, however the simpler, smaller scale systems are more successful when co-digestion with animal manure is used. The animal manure improves the C/N ratio of the feedstock and aids the anaerobic digestion process, allowing a more simple process to be used.

One small scale system that has been identified as having potential for application in Thailand is the Rottaler Model. This appears to be a flexible design that can be sized to suit the situation, without adversely affecting the process performance.

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Appendix 1

IEA Bioenergy Anaerobic Digestion Activity 1997 Report, Systems and Markets Overview of Anaerobic Digestion.

Appendix 2

Background Information on Biogas System for digestion of Municipal Solid Waste.

The following summarizes the information collected during the course of this study on the technical details of Anaerobic Digestion of MSW.

Digester Material

Anaerobic digestion occurs naturally wherever high concentrations of wet organic matter accumulate in the absence of dissolved oxygen. Only waste of organic origin can be processed in an anaerobic digester. As this makes up 30-60% of household waste there is a considerable benefit in diverting this waste from landfill. Municipal solid waste is composed of:-

- 1) Digestible Organic Fraction – Readily biodegradable organic matter, e.g. kitchen scraps, food residue, grass cuttings etc.
- 2) Combustible Fraction – Slowly digestible organic matter such as coarser wood, paper, cardboard. These are lignocellulosic materials which do not readily degrade under anaerobic conditions and are better suited to aerobic digestion, i.e. composting. (Opinions vary over the digestibility of paper, which depends on the lignin content, some forms of paper are much more digestible than others – generally only paper that is too contaminated with organic waste to be recycled, is considered for digestion). The combustible fraction also consists of indigestible n
- 3) Inert Fraction – Stones, glass, sand, metal, etc. Some of these products are suitable for recycling, the remainder can be landfilled.

Joint treatment of municipal solid waste with animal manure/sewage slurry is a popular method in existing plants, the process tends to be simpler and is economically more viable than an MSW only treatment system.

Separation

Source Separation: Recyclable materials separated from organic waste at the source.

Mechanical Separation: This can be used to separate an organic fraction of the waste if source separation is not available. The fraction obtained is more contaminated which will affect the heavy metal and plastic content of the final digestate composting product. In many countries compost derived from mechanical separation will not meet standards required for a soil conditioner product. – Ref 10.

Pre-treatment

Having separated any recyclable or unwanted materials from the waste, the organic material must be chopped or shredded before it is fed into the digester.

The organic matter is also diluted with a liquid, ranging from sewage slurry, to recycled water from the digestate, to clean water.

In some systems an aerobic pre-treatment allows organic matter to be partly decomposed under aerobic conditions before undergoing anaerobic digestion.

Anaerobic Digestion Process

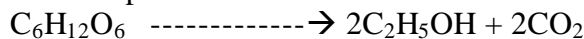
The process of digestion consists of three stages:

- 1) **Hydrolysis/Liquefication:** Involves the breakdown of insoluble, complex organic matter into simple, soluble molecules. Cellulose is depolymerised into sugars, alcohols, peptides, amino acids and fatty acids with the help of an enzyme released by the bacteria. In some processes this initial step is catalysed by the use of an acid or alkali.

In some industrial processes an hydrolysis process is added at the beginning stage to substantially degrade the hydrocarbon content of the solid waste before it is added to the digester. This provides a higher methane yield and gives a shorter digestion time. It also reduces the thick fibrous scum that can form on top of the digesting mixture and generally makes it less viscous and easier to process.

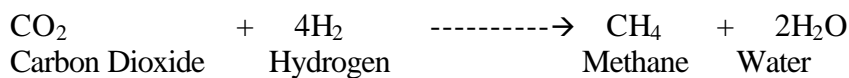
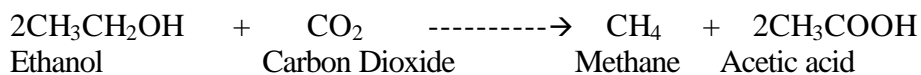
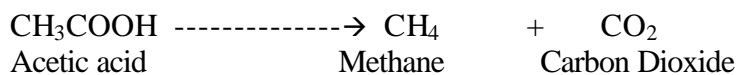
- 2) **Acetogenesis/Fermentation:** The simple monomer blocks formed in step 1 act as substrate feedstocks for the fermenting, acid forming anaerobic bacteria which produce various volatile acids, carbon dioxide and hydrogen. The principal acids produced in this process are acetic acid, propionic acid, butyric acid and ethanol.

For example:-



- 3) **Methanogenesis:** The acetic acid and hydrogen produced in step 2 are broken down by the acetoclastic methanogenic bacteria forming methane and hydrogen carbonate. Hydrogentrophic methanogenic bacteria then reduce the hydrogen carbonate with hydrogen to form methane. Many products, by-products and intermediate products are produced in the process of digestion before the final product of methane is produced.

Examples of some of the reactions that occur:-



Biogas Content

The gas produced contains methane, carbon dioxide, some inert gases and sulphur compounds. Typically 100-200m³ of gas is produced per tonne of organic MSW that is digested.

Typical Biogas composition:

Ref 10

Methane	55-70% by vol.
Carbon dioxide	30-45% by vol.
Hydrogen Sulphide	200-4000 ppm by vol.
Energy Content	20-25 MJ/m ³

Key Parameters

Anaerobic bacteria are sensitive to the climate within the digester. Methanogenic bacteria develop slowly and are sensitive to any change in physical or chemical conditions.

Biogas digesters can be used for many different types of organic materials but since they have different bio-chemical characteristics, their potential for gas production varies. The composition of the feedstock will affect both the yield and quality of the biogas.

Facilitating and inhibiting factors in the anaerobic process are defined below:-

C/N Ratio: The relationship between the amount of carbon and nitrogen present in organic materials is expressed in terms of the Carbon/Nitrogen ratio. A C/N ratio of 20 – 30 is considered to be optimum for an anaerobic digester.

If C/N ratio is very high, the nitrogen will be consumed rapidly by the methanogens to meet their protein requirement and will no longer react on the left over carbon content in the material. As a result the gas production will be low.

If the C/N ratio is very low, nitrogen will be liberated and accumulate in the form of ammonia. This will increase the pH value of the material. A pH value higher than 8.5 will start to show a toxic effect on the methanogenic bacterial population.

Animal waste, such as cow dung, which has been used successfully in biogas systems for many years, has an average C/N ratio of 24. Plant materials contain a high percentage of carbon and so the C/N ratio is high, (rice straw = 70, sawdust >200). Human excreta has a C/N ratio of about 8. To maintain the C/N level of the digester material at acceptable levels, materials with high C/N ratio can be mixed with those with a low C/N ratio, i.e. organic solid waste can be mixed with sewage or animal manure.

Examples of typical C/N values for various materials are shown below:-

Table 1: C/N Ratio of some Materials

Raw Material	C/N Ratio
Duck Dung	8
Human excreta	8
Chicken Dung	10
Goat Dung	12
Pig Dung	18
Sheep Dung	19
Cow Dung	24
Water Hyacinth	25
Municipal Solid Waste	40
Elephant Dung	43
Maize Straw	60
Rice Straw	70
Wheat Straw	90
Saw dust	>200

Ref 1

Dilution: Water or slurry can be added to the raw material to maintain the required consistency. If material is too diluted, the solid particles will settle down in the

digester and if it is too thick the particles will impede the flow of gas to the upper part of the digester. Different systems can handle different percentages of solid to liquid, average ratios are 10-25%, but some systems can cope with solids up to 30%. (ref 2)

pH Value: Optimum biogas production is achieved when the pH value of the input mixture is between 6 and 7. The pH value will be affected by mixture retention time in the digester. In the initial period of fermentation, large amounts of organic acids are produced and the pH value of the mixture can decrease to below 5. This will inhibit, or even stop, the digestion and fermentation process. The methanogenic bacteria are very sensitive to pH value and will not thrive below a value of 6.5. As digestion continues and the concentration of ammonia increases, due to the digestion of nitrogen, the pH value can increase to above 8. When the methane gas production has stabilised, the pH will remain between 7.2 and 8.2.

When plant material is fermented in a batch system, the acetogenesis/fermentation stage is rapid, producing organic acids which reduce the pH and inhibits further digestion. Reduction in pH can usually be controlled by the addition of lime.

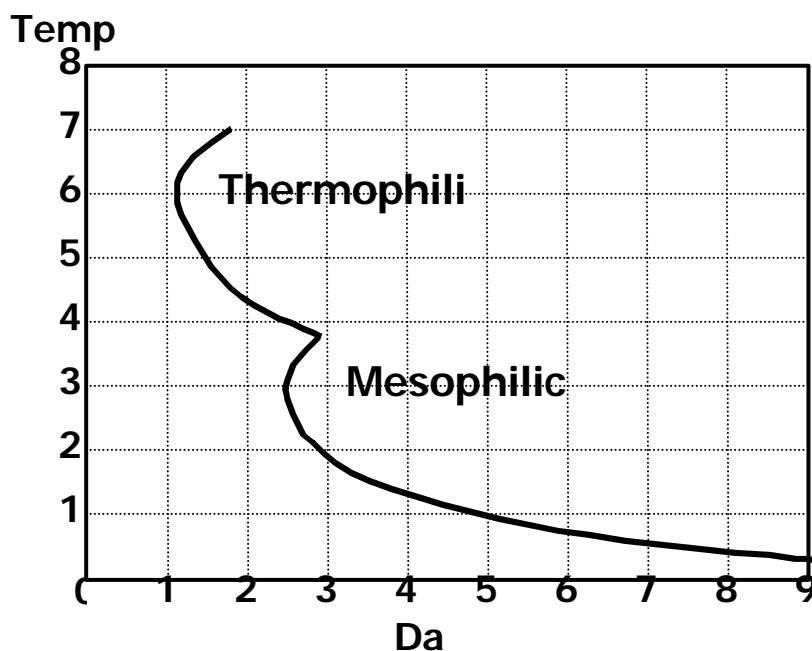
Temperature: Methanogenic bacteria is inactive at extremes of high and low temperature. When the ambient temperature goes down to 10°C, gas production virtually stops. Two temperature ranges provide optimum digestion conditions for the production of methane.

Mesophilic Range:- The mesophilic range is between 20 – 40°C, the optimum temperature is considered to be 30 - 35°C.

Thermophilic Range: - The thermophilic temperature range between 50 - 65°C produces a better rate of degradation.

Although the thermophilic process is more efficient, it is considered more complicated in respect of bacteria and the material required for tanks and pipes. Ref 6.

The graph below shows the general trend for the digestion time of a certain amount of organic matter vs temperature. (The curve may differ according to the physical/chemical composition of the feedstock) . Ref 10.



Loading Rate: This is an important process control parameter in continuous systems. Many plants have reported system failures due to overloading. This is often caused by inadequate mixing of the waste with slurry. If there is a significant rise in volatile fatty acids this normally requires that the feedrate to the system be reduced.

Retention Time: Wastes remain in a digester that is operating in the mesophilic range for a varying period of 10 – 40 days, the duration being dictated by differing technologies, temperature fluctuations and waste composition. (Ref 2).

Toxicity: Mineral ions, heavy metals and detergents are some of the toxic materials that inhibit the normal growth of bacteria in the digester. Small quantities of minerals, (sodium, potassium, calcium, magnesium, ammonium and sulphur), also stimulate the bacterial growth, but heavy concentrations will have a toxic effect. Heavy metals such as copper, nickel, chromium, zinc, lead are essential for bacterial growth in small quantities, but higher quantities will also have a toxic effect. Detergents such as soap, antibiotics, organic solvents also inhibit the bacteria. Recovery of digesters following toxic substances inhibiting the system can only be achieved by cessation of feeding and diluting the contents to below the toxic level.

Mixing/Agitation: Results from existing systems tend to show that a level of mixing is required to maintain the process stability within the digester. The objectives of mixing are to combine the fresh material with the bacteria, to stop the formation of scum and to avoid pronounced temperature gradients within the digester.

Over frequent mixing can disrupt the bacterial community and it is generally considered that slow mixing is better than rapid mixing. The amount of mixing required is also dependent on the content of the digestion mixture.

Health Issues: Bacteria and viruses present in municipal solid waste can be a risk to the workers handling the waste.

For a combination of sewage sludge and household waste, which are regarded as having a higher infectivity risk than animal manure, pre-treatment processing at 70°C for at least one hour is recommended by the Danish Energy Authority, in ref 3.

Solid residue/Slurry: After the biological degradation is complete the solid residue or digestate is removed and can be cured aerobically and screened for any unwanted items, (like glass shards, plastic pieces etc), before being used on the land.

The purity of the material fed into the system will dictate the quality of the slurry produced. This is used as a product to condition and improve soil.

Problems specific to MSW anaerobic digestion:

- 1) Nature of organic waste may vary according to location and time of year. In wet season horticultural plant cutting levels may be higher than in the dry season. This may lead to a variation in the C/N ratio and affect the rate of gas production.
- 2) Inadequate mixing of refuse and sewage can affect efficiency of system.
- 3) Blockage of pipes can be caused if large pieces of waste enter the system, this causes problems, particularly in continuous systems.

Advantages of MSW anaerobic digestion:

- 1) Makes landfills easier to manage by removing problematic organic waste material which is responsible for gaseous and liquid emissions.
- 2) Enclosed system allows all of the biogas to be collected, unlike on landfills where recovery only yields 30-40% of gas generated. Methane is a greenhouse gas with twenty times the impact of carbon dioxide.
- 3) An end product that can be used as a soil conditioner is produced.

Mixing the refuse with animal dung improves the system efficiency and allows for a more simple process design, improving the economic viability of the system. This is due to the improved nitrogen content that is achieved by mixing with dung.

Important points to be considered when designing a mixed MSW/animal dung or sewage Biogas system.

- 1) ***Health Issues:*** Bacteria and viruses present in municipal solid waste and human sewage can be harmful to those handling the waste and can remain in the slurry following the digestion process. Treatment of waste at 70°C for 1 hour is recommended, either before digestion or on slurry prior to use as a soil conditioner.
- 2) ***Sampling:*** It is useful to design into the digester system the ability to take samples of the digester material so that a check on the content can be maintained. This allows adjustments to be made to the content of the mixture if gas production reduces.
- 3) ***Gas Storage:*** Many existing animal dung biogas systems store the gas in a hemispherical concrete and brick structure, which forms the top of the digester unit. In some cases leakage from cracks in the concrete has been found. Attention should be paid to the construction of the concrete vessel or alternatively a steel vessel could be used for gas storage.
- 4) ***Agitation:*** Digestion rate is improved if a method of stirring is incorporated into the digester design.
- 5) ***Waste Content:*** The waste must be sorted so that all inorganic products are removed from the refuse prior to entry into the digester. Ideally the refuse should be sorted at source, if not, it could be sorted by hand on delivery to the site. However, at this stage recyclable materials are more likely to be contaminated with organic material and this is not desired for recycling.