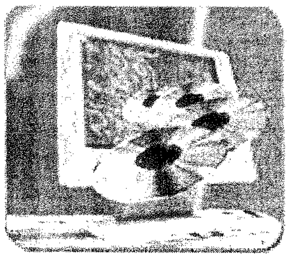
НАУЧНИ ПУБЛИКАЦИИ
ТОМ II. ЕКОЛОГИЯ
ЧАСТ 1



SCIENTIFIC PUBLICATIONS
VOLUME II. ECOLOGY
BOOK 1

www.ScienceBg.Net

Publishing by
Science Invest LTD – branch Bourgas, Bulgaria
- A Company of Union of Scientists in Bulgaria -
2003, Bulgaria, ISBN 954-90972-8-5

Редактори:
Доц. д-р Георги Йорданов
Доц. д-р Ангел Звездов
Съставил изданието: Иван Генов

****

The scientific articles
in the publication have been edited by:
Associate Professor Georgi Jordanov
Associate Professor Angel Zvezdov
The publication has been composed by: Ivan Genov

ISBN 954-90972-8-5

СЪВРЕМЕННИ ТЕХНОЛОГИИ НА АНАЕРОБНАТА ФЕРМЕНТАЦИЯ ПРИ БИОРАЗГРАДИМИ ОРГАНИКИ В ТВЪРДИ БИТОВИ ОТПАДЪЦИ

Иво К. Чуканов, Юлия К. Георгиева, Байко Д. Байков, Мила Д. Чуканова, Ботьо С. Захаринов,

Нов български университет, Департамент "Науки за Земята и околната среда"

гр. София, 1618, ул. Монтевидео № 21

MODERN TECHNOLOGY OF ANAEROBIC DIGESTION OF BIODEGRADABLE ORGANICS IN MUNICIPAL SOLID WASTES

Ivo K. Tchoukanov, Yuliya K. Georgieva, Bayko D. Baykov, Mila D. Tchoukanov, Botyo S. Zaharinov,

New Bulgarian University, Department of Earth and Environmental Sciences,

Sofia 1618, 21 Montevideo str., Bulgaria

Abstract

This study examined in depth the current status of the anaerobic digestion technologies for the treatment of the organic fraction of municipal solid wastes (MSW). Anaerobic digestion (AD) consists of the degradation of organic material in the absence of oxygen. It produces mainly 55 % methane and 45 % carbon dioxide gas and a compost product suitable as a soil conditioner.

The report compares various AD systems such as mesophilic vs thermophilic operation, low-solids vs high-solids feed, multi-stage vs single stage reactors, and AD systems treating mixed wastes vs biowaste. Much of the technology is based in Europe, with Germany and Denmark leading the field in technology.

The comparison between single stage, low-solids (LS) and single stage, high-solids (HS) operation indicates higher gas yields from high solids facilities. For example, the Waasa LS process reports 100 – 150 m^3 / ton of waste input and the Valorga HS process 220 – 250 m^3 / ton of feed to digester. In addition, the organic loading rate for single stage high-solids (e.g., DRANCO, 15 kg of Volatile Solids per m^3 per day) is twice that of the single stage low-solids (Waasa, 6 kg VS / (m^3 . d)).

Key words: *compost, anaerobic digestion, digestors, organic wastes, mesophilic operation, thermophilic operation, digestate*

Acknowledgements

This work is realized thanks to financial help of Contract No 43 / 20.05.2003, New Bulgarian University – Commission "Development of scientific research".

1. INTRODUCTION

Municipal solid waste (MSW) is the waste generated in a community with the exception of industrial and agricultural wastes. Hence MSW includes residential waste (e.g., households), commercial (e.g., from stores, markets, shops, hotels etc), and institutional waste (e.g., schools, hospitals etc). Paper, paperboard, garden and food waste can be classified in a broad category known as organic or biodegradable waste.

The organic compound fraction of MSW in the US represents 70 % of the waste composition and consists of paper, garden waste, food waste and other organic waste including plastics. The biodegradable fraction (paper, garden and food waste) accounts for 53 % of waste composition.

Therefore, treatment of these wastes is an important component of an integrated solid waste management strategy and reduces both the toxicity and volume of the MSW requiring final disposal in a landfill. This study explores the anaerobic digestion technology (AD), i.e. in the absence of oxygen, as one of the main options for processing the biodegradable organic materials in MSW.

The biodegradable fraction of MSW contains anywhere from 15 % – 70 % water. A representative average molecular formula for organic wastes, excluding nitrogen and other minor components, is $C_6H_{10}O_4$. The anaerobic decomposition of organic materials yields principally methane (CH_4), carbon dioxide (CO_2) and a solid compost material that can be used as soil conditioner.
This thesis examines in depth anaerobic digestion (AD) technologies in order to determine their economic and environmental competitiveness, as one of the options for processing the biodegradable organic materials in MSW.

A well-designed AD fosters sustainable development since it recovers energy thus reducing fossil fuel use and reducing greenhouse gas sources. It also allows nutrients in the form of compost product to be returned to the land maintaining nutrient closed loop system.

The advances of AD technology have been supported by legislation. Most European countries are aiming to limit MSW disposal to landfills to no more than 5 % of the collected material and have increased taxes on landfilling. This will ensure that waste is properly treated for combustibles and organics rather than being buried in the ground. The 15 % renewable energy by 2010 target as well as schemes such as "green pricing" in The Netherlands and some other European countries allow AD facilities to sell biogas for electricity generation at a premium. Similarly, in the United Kingdom, under the Non-Fossil Fuel Obligation (NFFO) act, electricity is sold at a premium from AD system.

Another factor that has triggered opting for energy recovery from waste is international agreements with respect to greenhouse gas emissions. Landfills are the source of large emissions of methane to the atmosphere and methane gas has a global warming potential (GWP) that is over twenty times that of carbon dioxide. Also, many utilities are very interested in earning credit for reducing GHG emissions. These utilities foresee the risk of mandatory GHG control imposed by future regulatory or legislative actions. Therefore, AD plants will be very attractive for utilities to earn GHG reduction credits. In future, the best practicable environmental option will be deriving energy from waste. Energy recovery technologies include combustion of waste and anaerobic digestion (AD). However, combustion of the wet stream of MSW does not provide efficient energy recovery. So the advantages offered by AD are worth exploring for the wet stream of Municipal Solid Waste (MSW) of New York City and elsewhere.

2. TYPES OF AD SYSTEMS

The methods used to treat MSW anaerobically can be classified into following categories:

Single Stage

Multi Stage

Batch

These categories can be classified further, based on the total solids (TS) content of the slurry in the digester reactor. Low solids (LS) contain less than 10 % TS, Medium solids (MS) contain about 15 – 20 % High solids (HS) processes range from about 22 % to 40 %. The single stage and the multi stage systems can be further categorized as single stage low solids (SSLS), single stage high solids (SSHS), multi stage low solids (MSLS) and multi stage high solids (MSHS). The drawback of LS is the large amount of water used, resulting in high reactor volume and expensive post-treatment technology. The expensive post treatment is due to de-watering required at the end of the digestion process. HS systems require a smaller reactor volume per unit of production but this is counterbalanced by the more expensive equipment (pumps, etc.) required. Technically, HS reactors are more robust and have high organic loading rates. Most AD plants built in the 80's were predominantly low solids but during the last decade the number of high solids processes has increased appreciably. There is substantial indication from the obtained data that high solids plants are emerging as winners.

2.1 Single Stage Process

Single stage reactors make use of one reactor for both acidogenic phase as well as methanogenic phase. These could be LS or HS depending on the total solids content in a reactor.

2.1.1 Single Stage Low Solids (SSLS) Process

Single stage low solids processes are attractive because of their simplicity. Also they have been in operation for several decades, for the treatment of sludge from the treatment of wastewater. The predominant reactor used is the continuously stirred tank reactor (CSTR). The CSTR reactor ensures that the digestate is continuously stirred and completely mixed. Feed is introduced in the reactor at a rate proportional to the rate of effluent removed. Generally the retention time is 14 – 28 days depending on the kind of feed and operating temperature.

Some of the SSLS commercial AD plants are the Wassa process in Finland, the EcoTec in Germany, and the SOLCON process at the Disney Resort Complex, Florida [28]. The plant examined in more detail is the Wassa process plant (10 % – 15 % TS) that was started in 1989 in Waasa, Finland. Currently there are three Wassa plants ranging from 3000 – 85000 tons per annum, some operating at mesophilic and others at thermophilic temperatures. The retention time in the mesophilic process is 20 days as compared to 10 days in the thermophilic. The feed used in this process is mechanically pre-sorted MSW mixed with sewage sludge. The organic loading rate (OLR) differs with the type of waste. The OLR was 9,7 kg / (m^3 day) with mechanically sorted organic MSW and 6 kg / (m^3 day) with source separated waste. The gas production was in the range of 170 Nm^3 CH_4 / ton of VS fed and 320 Nm^3 CH_4 / ton of VS fed and 40 – 75 % reduction of the feed VS was achieved.

The advantages offered by SSLS are operational simplicity and technology that has been developed for a much longer time than high solids systems. Also, SSLS makes use of less expensive equipment for handling slurries. The pre-treatment involves removing of coarse particles and heavy contaminants. These pre-treatment steps cause a loss of 15 - 25 % VS, with corresponding decrease in biogas yield. The other technical problem is formation of a layer of heavier fractions at the bottom of the reactor and floating scum at the top, which indicate non-homogeneity in the reacting mass. The bottom layer can damage the propellers while the top layer hinders effective mixing. This requires periodic removal of the floating scum and of the heavy fractions, thus incurring lower biogas yield. Another flaw is the short-circuiting, i.e. a fraction of the feed passes through the reactor at a shorter retention time than the average retention time of the total feed. This lowers the biogas yield and impairs hygienization of the wastes.

For the solids content to be maintained below 15 %, large volumes of water are added, resulting in large reactor volumes higher investment costs, and amount of energy needed to heat the reactor. Also, more energy and equipment are required for de-watering the effluent stream. The high investment costs associated with dilution and reactor volume plus the complex pre-treatment step offset the gains from the low cost equipment to handle slurry.

2.1.2 Single- Stage High Solids (SSHS) Process

The advances of the HS technology were the result of research undertaken in the 80's that established higher biogas yield in undiluted waste. Some of the examples of SSHS are the DRANCO, Kompogas, and Valorga processes. The DRANCO and Valorga processes are described in more detail later in this thesis. All three processes consist of a single stage thermophilic reactor (mesophilic in some Valorga plants) with retention time of 14 – 20 days.

In the DRANCO reactor, the feed is introduced from the top and digested matter is extracted from the bottom. There is no mixing apart from that occurring due to downward plug-flow of the waste. Part of the extracted matter is reintroduced with the new feed while the rest is de-watered to produce the compost product.

The Kompogas process works similarly, except the movement takes place in plug flow in a horizontally disposed cylindrical reactor. Mixing is accomplished by the use of an agitator. The process maintains the solids concentration at about 23 % TS. At solids content lower than 23 %, the heavy fraction such as sand and glass can sink and accumulate at the bottom; higher TS concentrations impede the flow of materials.

The design of the Valorga process is unique. The reactor is a vertical cylindrical reactor divided by a partial vertical wall in the center. The feed enters through an inlet near the bottom of the reactor and slowly moves around the vertical plate until it is discharged through an outlet that is located diametrically opposite to the inlet. Re-circulated biogas is injected through a network of injectors at the bottom of the reactor and the rising bubble result in pneumatic mixing of the slurry. The injectors require regular maintenance, as they are prone to clogging.

The high solids content in HS systems requires different handling, mixing and pre-treatment than those used in the LS processes. The equipment needed to handle and transport high solids slurries is more robust and expensive than that of the LS, comprising of conveyor belts, screws, and powerful pumps. On the other hand, the pre-treatment is less cumbersome than for LS systems. The HS systems can handle impurities such as stones, glass or wood that need not be removed as in SSLS.

Contrary to the complete mixing prevailing in SSLS, the SSHS are plug-flow reactors hence require no mechanical device within the reactor [9]. The economic differences between the SSLS and SSHS are small.

SSHS processes exhibit higher OLRs, as compared to SSLS; for example, OLR values of 15 kg VS/m ^{3} per day are reported for the DRANCO plant in Brecht, Belgium, where, whereas in the Waasa Process the OLR is 6 kg VS / m^3 per day. The biogas yield is usually high in SSHS as heavy fractions or the scum layer is not removed during the digestion.

There are pronounced differences between SSHS and SSLS reactors, in terms of environmental impacts. The LS process consumes one m 3 of fresh water per ton MSW treated whereas the water use in HS is one tenth of that [20]. Consequently, the volume of wastewater to be discharged is several-fold less for HS reactors.

2.2 Multi-Stage Process

The introduction of multi-stage AD processes was intended to improve digestion by having separate reactors for the different stages of AD, thus providing flexibility to optimize each of these reactions. Typically, two reactors are used, the first for hydrolysis / liquefaction-acetogenesis and the second for methanogenesis. In the first reactor, the reaction rate is limited by the rate of hydrolysis of cellulose; in the second by the rate of microbial growth. The two-reactor process allows to increase the rate of hydrolysis by using microaerophilic conditions (i.e., where a small amount of oxygen is supplied in an anaerobic zone) or other means. For methanogenesis, the optimum growth rate of microbes is achieved by designing the reactor to provide a longer biomass retention time with high cell densities or attached growth (also known as "fixed film reaction", where the microbes responsible for conversion of the organic matter are attached to an inert medium such as rock, or plastic materials in the reactor). An important requirement to be met in such reactors is removal of the suspended particles after the hydrolysis stage. Multi-stage processes are also classified as multi-stage low-solids (MMLS) and multi-stage high-solids (MMHS).

There is a lot of similarity, in terms of solids content, pre-treatment steps, handling of waste, requirement of water etc., between SSLS and MMLS as well as SSHS and MMHS processes.

2.2.1 Multi-Stage Low Solids Process

Some of the MSLS facilities are the Pacques process (Netherlands), the BTA process (Germany, Canada) and the Biocomp (Germany) process [28]. The Pacques process uses two reactors at mesophilic temperature. Initially, the feed consisted of fruit and vegetable waste but recently source-separated MSW is also being processed. The first reactor where hydrolysis occurs has solids content

10 %. Mixing is achieved by means of gas injection. The digestate from the first reactor is de-watered, and the liquid is fed to an Upflow Anaerobic Sludge Blanket reactor where methanogenesis occurs. The fraction of the digestate from the hydrolysis reactor is re-circulated with the incoming feed to the first reactor for inoculation. The remaining fraction is sent for compost production.

In the BTA process the solid content is maintained at 10 % and the reactors are operated at mesophilic temperatures. This process is described in detail in the case study section. It is very similar to the Pacques process except that the methanogenic reactor is designed with attached growth ("fixed film reaction") to ensure biomass retention. The effluent from the hydrolysis reactor is de-watered and the liquor is fed to the methanogenic reactor. This reactor receives only the liquid fraction from hydrolysis reactor to avoid clogging of the attached growth. At times, in order to maintain the pH within the hydrolysis reactor in the range of 6 – 7, the process water from the methanogenic reactor is pumped to the hydrolysis reactor.

The multi-stage low solids processes are plagued with similar problems to those of the SSLS reactors, such as short-circuiting, foaming, formation of layers of different densities, expensive pre-treatment. In addition, the MSLS processes are technically more complex and thus require a higher capital investment.

2.2.2 Multi -Stage High-Solids Process

The Biopercolat process is a multi-stage high-solids process but is somewhat similar to the Pacques process (MSLS) in that it consists of a liquefaction/hydrolysis reactor followed by a methanogenic Upflow Anaerobic Blanket Sludge reactor (UASB) with attached growth. However hydrolysis is carried out under high solids and microaerophilic conditions (where limited amount of oxygen is supplied in anaerobic zone). The aeration in the first stage and the attached growth reaction in the second provide for complete digestion at retention time of only seven days.

The advocates of multi-stage processes cite the advantages of high OLR for all types of multi-stage systems, such as 10 kg VS / (m^3 . d) and 15 kg VS / (m^3 . d) for the BTA (MSLS) and Biopercolat processes (MSHS), respectively. This is due to higher biomass retention with attached biofilm, which increases the resistance of methanogens to high ammonium concentrations. The biological stability thus achieved offers potential for increased OLR. However, high OLR does not result in high biogas yield. The lower biogas yield observed in practice is due to removal of solids that contain some biodegradable matter, after the short hydrolysis period before feeding the methanogenic reactor. In recent years, the single-stage systems have also achieved high OLRS thus canceling this advantage of multi-stage systems.

According to [9], commercial applications of multi-stage systems amount to only 10 % of the current treatment capacity, as will be discussed later, under current trends of AD systems.

2.3 Batch Reactors

Batch reactors are loaded with feedstock, subjected to reaction, and then are discharged and loaded with a new batch. The batch systems may appear as in-vessel landfills but in fact achieve much higher reaction rates and 50- to 100% higher biogas yields than landfills for two reasons. First, the continuous re-circulation of the leachate and second, they are operated at higher temperatures than landfills. There are three types of batch systems - single stage batch system, sequential batch system and an Upflow Anaerobic Sludge Blanket reactor.

The single-stage batch system involves re-circulating the leachate to the top of the same reactor. An example of such a system is the Biocel process in Lelystad, The Netherlands that was started in 1997 and treats 35,000 tons / y of source-sorted biowaste. The system operates at mesophilic temperatures and consists of fourteen concrete reactors each of 480m 3 capacity. The waste fed to these unstirred reactors is pre-mixed with inoculum. The leachates are collected in chambers under the reactors and recycled to the top of each reactor. The waste is kept within the reactor for over 40 days, until biogas production stops. The Biocel plant produces on the average 70 kg biogas / ton of source-sorted biowaste which is 40 % less than from a single stage low-solids digester treating similar wastes.

The sequential batch process comprises two or more reactors. The leachate from the first reactor, containing a high level of organic acids, is re-circulated to the second reactor where methanogenesis occurs. The leachate of the methanogenic reactor, containing little or no acid, is combined with pH buffering agents and re-circulated to the first reactor. This guarantees inoculation between the two reactors.

The third type of batch process is the hybrid batch-UASB process, which is very similar to the multi-stage process with two reactors. The first reactor is simple batch reactor but the second methanogenic reactor is an upflow anaerobic sludge blanket (UASB) reactor.

Batch processes offer the advantages of being technically simple, inexpensive and and robust. However, they require a large land footprint as compared to single-stage HS reactors since they are much shorter and their OLR two-fold less. Other disadvantages are settling of material to the bottom thus inhibiting digestion and the risk of explosion while unloading the reactor.

3. TRENDS IN AD TECHNOLOGY

According to the Bioenergy Report of the International Energy Agency (IEA), in 1996 there were about 90 AD plant around the world and 30 under construction (Table 1). This data includes all plants with treatment capacity of over 2500 tons per year. Around 40 companies are involved in marketing AD technology (Table 2). A 1999 report by the German Technical Cooperation Agency (GTZ) reports around 400 AD plants worldwide treating both municipal and industrial waste.

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

Table 1. Anaerobic Plants in various nations

Company	No. of plants in operation	No. of plants under construction
Arge Biogas, (Austrian)	2	0
Entech,(Austrian)	7	4
Kompagas,(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 UDHE, (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
Projectror, (Swedish)	2	0
Biocel / Heidermij Realisatie,(Dutch)	1	0
Ionics Italba,(Italian)	1	0
Kiklos, (Italian)	2	0

Table 2. Companies supplying AD plants of capacity >2,500 tons/year

The Biogasworks [26] shows a list of 130 plants and 45 and process suppliers of capacity varying from 500 to 300,000 tons / year and treating different waste streams. The distribution is presented in Table 3. It can be seen that most of the plants are operating in Europe (91 %), with some in Asia (7 %) percent and a few in the US (2 %). Germany is the leader with 35 % of all AD plants, followed by Denmark (16 %) and Sweden and Switzerland and Austria (8 %).

Country	Percent (%)
Austria	8
Belgium	8
China	2
Denmark	16
Finland	5
France	1
Germany	35
India	4
Italy	1
Japan	2
Netherlands	5
Poland	1
Spain	1
Sweden	2
Switzerland	8
Thailand	1
UK	1
Ukraine	1
USA	2

Table 3. Worldwide Distribution of AD Plants [26]

The survey of the state of art of AD, with respect to size, capacity and waste-streams and operating parameters, is based on data provided by [9]. The data included plants operating in Europe with capacity greater than 3000 tons / year. The trend shows that plant capacity and number of plants built annually increased rapidly since 1996.

Traditionally, AD plants have operated in the mesophilic range as it was difficult to control the temperature of digester at higher temperature; temperatures above 70° C, can kill the microbes digesting the waste. Along with the advent of high-solids AD, there has been progressing in using the thermophilic range. It is now an established technology and many plants are using it. The benefits offered are hygenizaion of waste, lower retention time and higher biogas yield [17].

Year	Cumulative capacity ton /year	
	Mesophilic	Thermophilic
till 1990	110 000	–
1991	120 000	–
1992	120 000	10 000
1993	120 000	45 000
1994	200 000	55 000
1995	200 000	90 000
1996	290 000	100 000
1997	300 000	198 000
1998	420 000	205 000
1999	505 000	310 000
2000	890 000	398 000

Table 4. Comparison between Mesophilic and Thermophilic AD Plants [9]

Industrial applications of single-stage high-solids and low-solids and are about the same. Initially, most AD systems were treating dilute wastes. However, more high-solids plants were constructed after 1998. Another advantage of high-solids systems is that they can process "mixed MSW" as well as biowaste. "Mixed MSW" is all material set out as garbage excluding recyclables, compostables or waste diverted from garbage by some other means. "Biowaste" is source separated household waste.

Year	Cumulative capacity ton /year	
	Low solids	High solids
till 1990	50 000	55 000
1991	50 000	55 000
1992	90 000	80 000
1993	100 000	80 000
1994	190 000	80 000
1995	205 000	80 000
1996	290 000	80 000
1997	300 000	90 000
1998	405 000	90 000
1999	700 000	180 000
2000	750 000	290 000
2001	880 000	450 000

Table 5. Comparison between Low Solids and High Solids AD Plants [9]

With regard to single-stage and multi-stage systems, the market has clearly chosen the former. As noted earlier in the thesis the survey [9] indicates that only 10,6 % of the current available capacity is provided by multi phase digestion systems.

Year	Cumulative capacity ton /year	
	Single stage	Multi stage
till 1990	90 000	55 000
1991	90 000	55 000
1992	100 000	55 000
1993	105 000	55 000
1994	190 000	55 000
1995	210 000	55 000
1996	350 000	55 000
1997	410 000	85 000
1998	580 000	105 000
1999	730 000	105 000
2000	910 000	105 000

Table 6. Comparison between Single Stage and Multi Stage AD Plants [9]

The development of AD systems had been in the treatment of source separated biowaste due to efficient collection system at household level. Recently, the interest has been to treat variety of wastes and led to increase in capacity of plants for mixed waste from 80000 ton/year in 1998 to

380000tons/year in 2001. AD demonstrates high flexibility in treating different waste-streams, from low solids to high solids and clean organic waste to grey waste [9]. The three DRANCO plants are examples of this flexibility to treat varied waste. Brecht plant not only treats biowaste collected from rural areas but also non-recyclable papers, diapers, paper napkins etc. High solids content is about 40 % whereas Salzburg plant operates at 30 % and treats biowaste. The waste composition for Bassum is mainly grey waste as well as food and non-recyclable paper.

Year	Cumulative capacity ton /year	
	Biowaste	Mixed MSW
1990	50 000	60 000
1991	50 000	60 000
1992	90 000	60 000
1993	100 000	60 000
1994	190 000	60 000
1995	205 000	60 000
1996	300 000	60 000
1997	405 000	80 000
1998	598 000	80 000
1999	700 000	180 000
2000	750 000	290 000
2001	875 000	440 000

Table 7. Comparison between AD plants treating Biowaste and Mixed MSW [9]

4. CASE STUDIES

4.1 Valorga Technology

The Valorga technology was developed initially in France and later by Steinmuller Valorga Sarl, a subsidiary of the German company Steinmuller Rompf Wassertechnik GmbH. The process was initially designed to treat organic MSW and was later adapted to the treatment of mixed MSW, biowaste (source separated household waste), and grey waste (organic residual fraction after biowaste collection) [22].

The Valorga process plant consists of essentially six units: waste reception and preparation unit, AD, compost curing, biogas utilization, air treatment, and an optional water treatment unit (when effluent is not treated in municipal wastewater treatment plant). The reception unit has a scale for weighing the trucks bringing in the organic materials. The waste is unloaded in a closed pit equipped with a foul air collection system. The feed material passes through an electromechanical system, designed according to the waste to be treated, that includes plastic bag opening and size reduction equipment. The waste is then conveyed and fed continuously to the AD unit.

In the AD unit, the waste is mixed with re-circulated leachate into a thick sludge of about 20-35% solids content, depending on the type of waste. Therefore, the water requirement is minimal. The digester operates either in the mesophilic range (e.g., Amiens plant) or the thermophilic range (Freiburg plant). The Valorga digesters are concrete vertical cylinders of about 20 meters height and 10 meters internal diameter. They are designed so as to maintain plug flow through the reactor. They are equipped with a vertical partition in the center that extends over 2/3 of the diameter and over the full height of the reactor. This inner partition minimizes short-circuiting of the sludge and ensures plug flow through the entire volume of the reactor. The orifices for introducing feed and removing digestate are located on either side of the inner wall. Mixing of the fermenting material is provided by a pneumatic system i.e. biogas at high pressure is injected through orifices at the bottom of the reactor and the energy of the rising bubbles serves to mix the sludge.

There are no mechanical parts and maintenance consists of periodic cleaning of the nozzles at the bottom of the digester

Plant	Plant Start-up Year	Waste Type	Treatment capacity (Ton / year)	Digester Volume (m^3)	Gas Yield Nm^3 / ton input digestion	Biogas end-use	Compost Use
Amiens, France	1988 1996	MSW MSW	85,000	3*2400 1*3500	140 – 160	High pressure steam for industrial use (5500 kW)	Agriculture
Engels-kirchen (Germany	1998	Biowaste	35 000	2*3000	100 – 110	Heat & electricity (940 kW)	Agriculture
Tilburg, Netherlands	1994	Biowaste Or Biowaste + Paper	52 000 Or 40 000 + 6000	2*3300	80 – 85	Biogas treated and injected into Tilburg City distribution network	Agriculture
Hanover, Germany	Start-up 2002	MSW + sewage sludge	100 000 + 25 000	3*4200	90	Heat & electricity	Landfill according to new legislation
Bottrop, Germany	1995	Biowaste	6500	1*1000	100 – 120	Heat & electricity	Agriculture
Varennes-Jarcy, France	2001	MSW + biowaste	100 000	2*4200 1*4500	110 – 120	Electricity	Agriculture
Cadiz, Spain	2000	MSW	115 000	4*4000	145	Heat & electricity	Agriculture
Geneva, Switzerland	Start up phase	Biowaste	10 000	1*1300	110 – 120	Heat & electricity	Agriculture
Mons, Belgium	2000	MSW + biowaste	23 000 + 35 700	2*3800	110 – 120	Heat & electricity	Agriculture
Freiburg*, Germany	1999	Biowaste	36 000	1*4000	110-120	Heat & electricity	Agriculture
Bassano, Italy	Start up in 2002	MSW + Biowaste + Sludge	44 200 + 8200 + 3000	3*2400	129	Heat & electricity	NA
Barcelone-Ecoparque Spain II	Start up in 2003	MSW	120 000	3* 4500	114	Heat & electricity	NA
La Coruña, Spain	2001	Mixed MSW	182 500	4*4500	130 – 150	Heat & electricity (5 *1250 kW)	NA

* thermophilic operation

Table 8. Operating Valorga plants [22]

The digested material exiting the reactor goes through a filter press that separates the compost material from the leachate solution. The leachate is reused for diluting incoming waste and any excess is transferred to the water treatment unit or the municipal sewage network. The filter cake is transferred to composting piles where it is subjected to curing in a closed building for about two weeks. Stones and other inert materials are removed. The compost product is considered to be of high quality and is sold as soil conditioner.

The biogas produced is used to generate electricity and steam or is fed to the city gas network. The biofilters and the water treatment facilities ensure that the Valorga plants control all air and water emissions and meet local regulations.

Valorga operates about 10 plants in Europe treating a variety of wastes but mostly the organic fraction of MSW. The compost is used in agriculture and the biogas is used to provide heat and electricity. The Valorga Tilburg plant is described in the following section.

4.1.2 The Valorga plant at Tilburg, Netherlands

The Tilburg plant began its operation in 1994 and treats primarily vegetable, garden and fruit waste (VGF). The plant capacity is rated at 52 000 tons / year of VGF, or 40 000 tons VGF plus 6000 tons of non-reusable paper and cardboard. A central refuse treatment company collects and separates municipal waste from the participating 20 municipalities. The feed consists of 75 % kitchen and garden waste and 25 % paper, cardboard. The annual rate of MSW generation in the Netherlands is nearly 450 kg per capita. Thus, the estimated amount of VGF generated by the Tiburg population of 380,000 is 64,000 tons of VGF per year.

The plant consists of two digesters, each of 3300m 3 capacity, and produces 2,8 million m^3 of methane per year (70 m^3 / ton). The waste is sheared to less than 10 cm particles before being fed to digestion unit. The retention time in this plant is 20 days at a mesophilic temperature of 38° C. The biogas production can be up to 106 m^3 per ton of waste, some of which is pressurized and pumped back into the reactor to improve mixing. The biogas product is piped to an upgrading plant, where it is refined to natural gas quality and then supplied to the municipal network. The biogas contains 56 % CH_4 and has a calorific value of about 20 MJ / m^3 while the refined gas contains 31,7 MJ / m^3 [10]. Gas refining consists of compressing, cooling, scrubbing, and drying. The methane gas after undergoing refining is fed to the municipal grid. The Tilburg facility highlights the technical and economic feasibility of using energy from waste in the form of biogas to generate electricity. The compost product amounts to 28 000 tons / year and is reported to be of high quality for agricultural use.

A technical report produced by the Center for Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) [5] analyzed the economic and environmental performance of the Tilburg facility between 1994 and 1999. CADDET reported that the natural gas yield was about 50 m^3 / ton. The net yield of natural gas, i.e. after providing for heating and electrical energy for the plant, was 1,360,000 m^3 of methane per year, i.e. about 44 m^3 of methane per ton of organic material processed. The economic analysis by CADDET [10] reported that the capital investment for the Tilburg plant was equivalent to $17,500,000. This corresponds to $440 per yearly ton processed currently or $146,000 per daily ton of capacity. For comparison, the capital cost of a large size Waste-to-Energy plant (combustion of MSW) amounts to about $120,000 per daily ton of MSW processed.

The main sources of revenue of this plant are the "tipping" fees paid by the municipalities for waste treatment and the sale of natural gas. Between 1994 and 1999, the average fee for waste treatment was $90 / ton resulting in the average annual revenue of $3,600,000 per year. Assuming an average gas price of $0,06 / m^3 [10], the gas revenues were $81,600 per year.

Assuming an administrative and operating personnel of twenty and an average wage and benefits cost of $40,000 per person, the labor cost is estimated at $800,000. Assuming an equal amount for all other costs (maintenance, supplies and materials, etc.), adds another $800,000. For an assumed 20-year life of the plant and at 10 % required return on investment, the annual capital charge for repayment of the

$17,5 million principal is calculated to be $920,000. Subtracting these three cost items from the annual revenues of $3,68 million, results in a net annual income of $1,16 million. It can be seen that under the above assumptions the Tilburg operation is profitable.

The environmental performance of the Tilburg indicates that 1,36 million m^3 of methane per year are recovered and used for electricity generation. This corresponds to 728 tons of carbon in the form of CH_4. Considering that one ton of C as methane is equivalent to 21 tons of C as carbon dioxide the Tilburg operation avoids landfill emissions of about 15,000 tons of carbon equivalent.

4.2 The DRANCO Process

The DRANCO process is a proven a high-solids single-stage AD system. It treats various waste streams such as biowaste, mixed waste, industrial organics, paper waste, market waste, rural waste, manure, sewage sludge, and others. The process operates at 50 – 58° C with retention time 20 days [19]. The feed is introduced continuously through the top of the reactor and digested material is removed from the bottom continuously. This stream is de-watered in a screw press and the filter cake is cured for two weeks to produce a compost product. There is no mixing in the reactor apart from the downward plug flow of the waste due to gravity. The filtrate obtained from de-watering is re-circulated and used to adjust the solids concentration of incoming waste. The compost product is marketed as "Humotex" and is used for soil amendment. The biogas yield is between 100 – 200 m^3 / ton of waste and is used to provide electricity and heat. About 50 percent these are used by the plant and the rest sold.

There are seven DRANCO plants (Table 9) operating in Europe with capacity ranging from 10,000 to 35,000 tons / year. The plant discussed in detail in the following section is the Brecht plant in Belgium (capacity 12 000 tons / year).

Country	City	Year	Capacity (Ton/Year)	Waste Type
Belgium	Brecht	1992	12 000	Biowaste/non recyclable paper
Austria	Salzburg	1993	13 500	MSW/Sewage sludge
Switzerland	Aarberg	1997	11 000	Biowaste
Germany	Bassum	1997	13 500	Grey Waste
Germany	Kaiseser--slautern	1998	20 000	Biowaste
Switzerland	Villeneue	1998	10 000	Biowaste
Belgium	Brecth	1998	35 000	Biowaste

Table 9. Operating DRANCO Plants [29]

4.2.1 The Brecht Plant

The Brecht plant in northern Belgium started operation in 1992 and is treating 12,000 tons / year. Food, yard trimmings and non-recyclable paper wastes are collected from 26,000 households. The source-separated MSW collected is weighed and unloaded at the plant. Undesirable materials like stones are removed and then the waste is shredded in a rotating trommel. The waste is fed to the digester of capacity of 808 m^3 (7 m diameter, 21 m height). The retention time is 12 – 20 days at 50 – 58° C (thermophilic range).

The generated biogas is used in a 290 kilowatt generator to produce electricity of which 40 % is used on-site and 60 % is sold to the local power grid. At times, the biogas has to be flared as power cannot be sold into the grid after 10 p.m. The digested material is de-watered and cured aerobically for about 10 days in a facility where in-floor ducts provide airflow and the compost is turned periodically by mechanical means. According to an economic analysis [29], the investment costs for this plant were $6,1 million. This corresponds to $500 per yearly ton processed currently or $170,000 per daily ton of capacity. The revenue from waste treatment amounts to $122 per ton of feed. The compost is sold for $13 per ton. Sinclair and Kelleher [29] estimated that a similar facility processing 25,000 tons per year would cost approximately $14,3 million.

This would correspond to $570 per yearly ton processed currently or $190,000 per daily ton of capacity.

	Quantity (tons)
Compost product	0,3
Biogas	0,13
Wastewater	0,32
Residue	0,2
Costs and revenues	
Item	Millions of dollars
Investment Cost	$6,1
Administrative & Labor Cost	$0,24 / year
Operational Cost	$0,24 / year
Annual Charges	$0,32 / year
Revenue	$122 per ton / feed
Compost	$13 per ton /compost
Total Revenue	$1,51 million per year

Table 10. Brecht AD facility outputs per ton of feed material [29]

Using the data for the plant (Table 10), the total revenue from treating the waste and selling compost amounts to $1,510,800 per annum. Using the similar assumptions as was for the Tilburg plant, with the exception that since the capacity of the Brecht plant is 2/3 that of Tilburg, the annual labor cost is estimated at $240,000 and all other costs, such as maintenance, supplies and materials, at $240,000. For an assumed 20-year life of the plant and at 10 % required return on investment, the annual capital charge for repayment of the $6,1 million principal is calculated to be $320,000. The net annual income of $710,800 is obtained after subtracting the labor cost, operational cost and annual capital charges. The positive net income indicates that the plant operation is profitable.

4.3 The low-solids, multi-stage Biotechnische Process

Biotechnische Abfallverwertung GmbH (BTA) of Munich, Germany developed in the 1980s a multi-stage low-solids system for treating mixed waste (all MSW except materials that are currently recycled or composted,) or source separated organic waste (food and garden waste). Germany has BTA plants operating in five municipalities. A research and development facility is located in Baden, Germany. BTA is also operating in other parts of Europe, and in Asia and North America. The BTA process is marketed as both single stage (e.g., Dietrichsdorf plant) as well as multi-stage process. There are eight BTA plants (Table 11) operating with capacity ranging from 1000 to 150,000 tons/year. The plant discussed in detail in the following section is the Newmarket plant in Canada (capacity 150,000 tons / year).

Location	Year	Capacity (Tons/year)	Waste Type
Newmarket (Canada)	Started in July 2000	150,000	Biowaste commercial waste organic sludges
Mertingen (District Donau-Ries)	Operation in spring 2001	1,000	Biowaste
Wadern-Lockweiler (Saarland)	–	20,000	Biowaste commercial waste
Erkheim (District Unterallgäu)	–	11,500	Biowaste commercial waste
Kirchstockach (Munich District)	Start-up in 1997 as MS digestion	20,000	Biowaste
Karlsruhe	Start-up in 1996. On a landfill area; automated feeding system; biogas utilisation.	8,000	Biowaste
Dietrichsdorf (Kelheim District)	Start-up in 1995 as SS digestion	17,000	Biowaste commercial waste
Elsinore* (Denmark)	Start-up in 1991 as MS digestion	20,000	Biowaste
Garching**	Operated 1986 till 1998. Used for tests in the area of R & D	6**	Tested various waste streams

*** Temporarily not in operation**
**** Pilot Plant with capacity ton / week – information not available**

Table 11. Operating BTA Plants [27]

BTA combines sophisticated waste pre-treatment and separation techniques within a fully enclosed and highly automated facility. The two unique steps of BTA process are "hydropulping," a process that removes contaminants (plastic, glass, and metals) and homogenises the waste, thus producing an organic suspension that flows through a "hydrodynamic de-gritting system," to remove any remaining shards of glass, small stones or sand [27].

4.3.1 The BTA Newmarket Plant

The plant is located in Newmarket, Ontario, Canada and has a capacity of 150,000 metric tons of organic waste per year. It started operation in July of, 2000 on a 2,2 ha (5,4 acres) site.

The facility receives the mixed waste brought in by collection vehicles that unload on the tipping floor. From there, the waste is conveyed to a pre-sort station, where oversized, contaminants as well as recyclables are removed. After the pre-sort station, the material continues through a trommel screen that separates fine materials (mostly organic), medium sized materials (mostly containers) and large objects such as newspaper, cardboard, film, plastic and textiles. The front end of the screen is equipped with a series of knives to rip open plastic bags. A manual sorting station sort plastics (PET, HDPE), glass and textiles. Also magnetic and eddy current separators are used to extract ferrous metals and aluminum cans. The marketable materials are sent for recycling and the non-recyclables are landfilled, while the organic-rich materials are fed to a 32-cubic-metre capacity hydropulper where they are mixed with water over a 16-hour processing period. The hydropulper creates an organic suspension and removes non-organic material that may have escaped pre-sorting and can be either "lights" or "heavies". The light fraction, is removed by a hydraulic rake attached to the hydropulper while the heavy fraction is captured through a sieve at the base of the hydropulper.

The hydrocyclone, or hydrodynamic de-gritting system, removes the sand and grit left in the organic pulp after hydropulping. The removed sand and grit are sent to landfill. The remaining pulp goes to the anaerobic digester where it is subjected to add for 15 days. The digestate is de-watered in a screw press and the filtrate is re-circulated to the hydropulping process. The filter cake is subjected to curing for 20 days. The 60,000 tons of compost produced annually are bagged and distributed to retail horticultural outlets. When the compost material does not meet the prescribed standards, it is l used for quarry restoration and other land rehabilitation projects.

The produced biogas is used to provide electrical and thermal energy for the facility. The biogas fuels an 820 KW co-generation generator installed at Newmarket. About 5,000 MWh of electricity is produced annually of which the plant uses 2MWh and the rest sold to the local grid and supplies 3,000 homes is sold to grid [27].

5. POTENTIAL FOR USE OF AD TECHNOLOGY TO TREAT NYC ORGANIC MSW

New York City (NYC) in 2001 generated 4,5 million tons per year of MSW. Most of this waste finds its way into landfills [30]. For half a century, the Fresh Kills landfill in Staten Island provided a dumping ground for New York City's MSW. With the closing of this site in 2001, NYC is facing a critical problem of waste disposal. This part of the study explores the possibility if AD can ease some of the burden of NYC waste especially organic MSW.

After the closure of the Fresh Kills, NYC in its long term and short-term waste management plan depends heavily on exporting waste to out of state landfills. This puts NYC at the mercy of legislation that presently is allowing the interstate transport of MSW. NYC will have to rethink its waste disposal policy if legislation passed forbidding exportation of waste. Furthermore, NYC continues to depend on landfill while most of the European countries are moving away from it. The legislation in these European countries targets no or minimal organic MSW to landfills. The organic content constitutes about 55 % of NYC MSW which includes paper, wood, textiles, food waste, yard waste and miscellaneous organics (Table 12).

Waste Component	% Weight
Paper	31,3
Corrugated Cardboard	4,7
Newspapers	9,2
All other papers	17,4
Plastics	8,9
HDPE (clear or color)	1,1
Films and Bags	4,8
PET	0,5
Polypropylene, polystyrene	0,9
PVC	0,1

All other plastics	1,4
Wood	2,2
Textiles	4,7
Rubber & Leather	0,2
Fines	2,3
Other Combustibles	2,3
Food Waste	12,7
Yard Waste	4,1
Disposable Diapers	3,4
Miscellaneous	7,8
Glass	5,0
Clear Glass Containers	2,9
All other glass	2,1
Aluminum	0,9
Ferrous Metal	3,9
Hazardous Waste	0,4
Bulk Items (appliances, furniture etc)	9,9

Table 12. Composition of NYC Waste [21]

The waste management options include recycling and waste disposal means could be combustion and composting. The more biodegradable organic fraction or the wet stream such as food and yard waste constitutes19,4 % i.e. 873,000 tons per year (Table 12). The rest of the stream, also known as the dry stream, comprising paper, plastics, metals and glass can be recycled or combusted but. The waste disposal option open for wet stream is combustion and aerobic or anaerobic composting. However, combustion of wet stream does not provide much energy from the wet stream due to its high moisture content. According to [21], the calorific value of food and yards waste is only 5350 kJ / kg (2300 BTU / lb) and of this about 2600 kJ of heat is wasted per kg of water in the feed [21].

Apart from combustion, the only way to deal with the organic fraction of MSW is aerobic composting (bioconversion in the presence of oxygen) or anaerobic digestion (AD). Aerobic composting is a net energy user rather than energy generator. A study by a Dutch team [5] that compared an aerobic composting plant with the Tilburg AD facility showed that the AD plant produced 366 MJ of net energy per ton of waste whereas the composting plant consumed 261 MJ per ton. The advantage of energy generation combined with the global movement towards reduction in fossil fuel usage will make AD increasingly attractive.

As described earlier in the thesis, the capacity of an AD plant can be increased by the addition of a reactor to the existing facility. To treat 873,000 tons of waste per year, NYC can implement a facility based on the Valorga process, that consists of four reactors with digester volume 4* 4500 m^2 of the type used at La Coruña (Spain) treating 182,500 tons of mixed MSW per year. On the basis of data from the La Coruña plant assume generation of methane from the hypothetical NYC plant would amount to 78 570 000 m^3 per year (90 m^3 per ton of feed). On the basis of the cost data presented earlier for Valorga plant, the capital cost of a NYC plant of 900,000 tons capacity is scaled up in terms of 2002 dollars (assumed annual inflation between 1994 and 2002 at an average of 3 %) is estimated at about $500 062 500. This corresponds to $572 per yearly ton processed currently or $209 075 per daily ton of capacity. Assuming revenue sources are "tipping" fees paid by the municipalities for waste treatment and the sale of natural gas. Between 1994 and 1999, the average fee for waste treatment was $90 / ton resulting in the average annual revenue of $3,600,000 per year. Assuming an average gas price of $0,06 / m^3 [5], the gas revenues were $4 714 200 per year.

Using similar assumptions as for Tilburg plant the administrative, labor and operating expense is estimated at $1 600 000. However, considering the NYC plant will be treating 873 000 tons per year (22,5 times waste treatment) the expense amounts to $36 000 000. Further assuming 20-year life of the plant and at 10 % required return on investment, the annual capital charge for repayment of the $500 062 500 principal is calculated to be $2 600 000. Subtracting the expenses from the annual revenues of $83 284 200, results in a net annual income of $44 684 200 a profitable operation. The environmental performance on the basis of 78 570 000 m^3 of methane per year recovered and used for electricity generation. This corresponds to 40 000 tons of carbon in the form of CH_4. Considering that one ton of C as methane is equivalent to 21 tons of C as carbon dioxide the NYC operation avoids landfill emissions of about 840 000 tons of carbon equivalent.

6. CONCLUSIONS

In the last decade of the 20 th century, the use of AD technology for the processing of organic wastes has expanded appreciably. Between 1996 and 2000 the number of new AD plants increased from 2 to 7 plants per year. Europe is far ahead in AD technology and Germany and Denmark are leading in the use of AD technology.

AD technology has seen remarkable progress in reactor and process design. Earlier, long periods of time were required for complete degradation. Mesophilic temperatures (about 35° C) would require up to 30 days for digestion. The development of thermophilic (60 – 65° C) AD has reduced the retention time for solids in the digester to less than 15 days. An example of this change is one of the Valorga plants where the retention time of 28 days was reduced to 14 days by means of thermophilic operation.

AD plants have also made much progress in their capacity to treat a wide range of waste streams. In late 70's, most of the AD plants were designed to treat sewage and were predominantly low-solids operations. However, during the last decade the number of high solids processes has increased appreciably to include organic MSW treatment. If one of the goals of new plants is energy generation, then high solids are more promising. The DRANCO and Valorga case studies are representative of good strategies for obtaining revenues by supplying energy to nearby operations and by creating a market for compost. For example, the Tilburg plant (40,000 tons / year MSW capacity) has an estimated annual income of $1,16 million. The advantages offered by HS includes higher methane production (Valorga, 220 – 250 m^3 / ton of feed) as compared with LS operations (Waasa, 100 – 150 m^3 / ton of feed). In addition, the reported organic loading rate for HS (DRANCO, 15 kg VS per m^3 per day) is about twice that of LS (Waasa, 6 kg VS / (m^3 . d)).

Single stage AD processes are starting to dominate the market because of their simple reactor design and low investment and operational costs. The batch system would be right for developing countries for these are cheap and easy to operate. Even though large land acerage is required which is not a problem in rural areas say for India. Also the AD system fits well for them as it generates biogas and their dependence on fuel wood gets reduced.

The advances of AD technology have been supported by legislation. Most European countries are aiming to limit MSW disposal to landfills to no more than 5 % of the collected material and have increased taxes on landfilling. This will ensure that waste is properly treated for combustibles and organics rather than being buried in the ground. The 15 % renewable energy by 2010 target as well as schemes such as "green pricing" in The Netherlands and some other European countries allow AD facilities to sell biogas for electricity generation at a premium. Similarly, in the United Kingdom, under the Non-Fossil Fuel Obligation (NFFO) act, electricity is sold at a premium from AD system.

Another factor that has triggered opting for energy recovery from waste is international agreements with respect to greenhouse gas emissions. Landfills are the source of large emissions of methane to the atmosphere and methane gas has a global warming potential (GWP) that is over twenty times that of carbon dioxide. Also, many utilities are very interested in earning credit for reducing GHG emissions.

These utilities foresee the risk of mandatory GHG control imposed by future regulatory or legislative actions. Therefore, AD plants will be very attractive for utilities to earn GHG reduction credits.

In future, the best practicable environmental option will be deriving energy from waste. Energy recovery technologies include combustion of waste and anaerobic digestion (AD). However, combustion of the wet stream of MSW does not provide efficient energy recovery. So the advantages offered by AD are worth exploring for the wet stream of Municipal Solid Waste (MSW) of New York City and elsewhere.

REFERENCES

1. AD-NETT Technical summary, Economics of Anaerobic Digestion of Agriculture Waste, Technical Summary, October 1998, Ian Higham, AEA Technology Environment.

2. AD-NETT Technical summary, Environmental Aspects of Biogas Technology written by Barbara Klingler, German Biogas Association.

3. Aumônier, S. (1997). Life Cycle Assessment of Anaerobic Digestion: A Literature Review. RDA/SR-97002. Washington, DC: Resource Development Associates.

4. Brinkman, J., Baltissen, T, and Hamelers, B. (1997). Development of a Protocol for Assessing and Comparing the Quality of Aerobic Composts and Anaerobic Digestates. RDA/SR-97001. Washington, DC: Resource Development Associates.

5. Center for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) Center for Renewable Energy, UK, (1998), Upgrading of Biogas to Natural Gas Quality, Technical Brochure No 154.

6. Chandler, A., Jewell, W., Gossett., M., Van Soest, J., Robertson., B. (1980) Predicting Methane Fermentation Biodegradability, Biotechnology and Bioengineering Symposium, No 10, 93-107.

7. Cecchi, F., Traverso, P.G., Mata-Alvarez, J., Clancy, J., Zaror, C. (1988) State of the Art of R&D in the Anaerobic Digestion of Municipal Solid Waste in Europe, Biomass, No 16, pp. 257-284.

8. De Baere, L., Verstraete, W. (1985) Anaerobic fermentation of semisolid and solid substrates, Laboratory of Microbial Ecology, pp 195-208, State University of Ghent, Belgium.

9. De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, Water, Science Technology Vol. 41, No 3, pp 283-290.

10. Fruteau de Laclos, H., Desbois, S. and Saint-Joly, C. (1997) Anaerobic digestion of Municipal Solid Organic Waste: Valorga full-scale plant in Tilburg, The Netherlands. Water, Science Technology Vol. 36, No 6-7, pp 457-462.

11. Haug, R.T. (1993) The Practical Handbook of Composting Engineering, Chapter 2, pp 10, Lewis Publishers.

12. IEA Bioenergy AD Activity 1997 Report, Systems & Markets Overview of AD.

13. Lagerkist, A., Chen, H. (1993) Control of Two Step Anaerobic Degradation of Municipal Solid Waste (MSW) by enzyme addition, Water, Science Technology Vol. 27, No 2, pp 47-56.

14. Liu, T., Ghosh, S., (1997) Phase Separation During Anaerobic Fermentation of Solid Substrates in an Innovative Plug-Flow Reactor, Water, Science Technology Vol. 36, No 6-7, pp 303-310.

15. Lusk, P., Moser, M. (1996). "Anaerobic Digestion – Yesterday, Today and Tomorrow." Ninth European Bioenergy Conference; June 24-27, 1996, Copenhagen, Denmark. UK: Pergamon Press; pp. 284-289.

16. Metcalf & Eddy (1985), Wastewater Engineering: Treatment, Disposal & Refuse, Mc Graw-Hill.

17. National Renewable Energy Laboratory (NREL), Colorado, US (1992) Data Summary of Municipal Waste Management Alternatives, Volume X.

18. Pavan, P., Battistoni, P., Cecchi, F., Mata-Alvarez, J., (1999) Two-Phase Anaerobic Digestion of Source Sorted Organic Fraction of Municipal Solid Waste (OFMSW) Performance and Kinetic Study, Water, Science Technology Vol. 41, No 3, pp 111-118.

19. Regional Information Service Centre for South East Asia on Appropriate Technology (RISE-AT) (Nov 1998), Review of current status of Anaerobic Digestion Technology for treatment of MSW.

20. Southern Sydney Waste Board, Pre-Treatment and Stabilisation Study, Final Report, Nolan- ITU PTY Ltd., May 1999.

21. Themelis, N.J., Kim, H.Y., Brady, Mark., (2001) Energy Recovery from New York City solid wastes

22. The Anaerobic Digestion and the Valorga Process, Jan 1999, Literature and brochures provided by the company.

23. U.S. Environmental Protection Agency, Characterization of Municipal Solid Waste in the US 1996 Update, Report No. EPA530-R-97-015, (June 1997) Franklin Associates, Ltd.

24. U.S. Environmental Protection Agency, Municipal Solid Waste in the US 1999: Facts and Figures, Municipal and Industrial Solid Waste Division Office of Solid Waste.

25. www.add-net.com

26. www.biogasworks.com

27. www.canadacomposting.com

28. www.soton.ac.uk

29. www.ows.be

30. www.columbia.edu.cu.earth