Appendix 5: Supplemental Information on Residual Waste Processing Technologies

BIOLOGICAL TREATMENT

Even the most successful waste recycling strategies involving source-separated organics and recyclables will still have a residual waste stream that needs to be treated to avoid landfill disposal. The residual waste stream can be dealt with in several ways but a technology which has become increasingly popular is mechanical-biological treatment (MBT). The term describes the integration of processes normally found in material recycling facilities (MRF), refuse derived fuel (RDF) plants, and composting plants.

Mechanical-Biological Treatment (MBT)

There are two different approaches to MBT. In the so-called *separation or splitting* approach, only the organic rich fraction is treated biologically and the rest is used as fuel in a RDF plant or is landfilled. The second method is the *mixed or joint flux stabilisation* process in which all of the residual waste is treated biologically with subsequent splitting of the stabilized waste into streams for use as RDF fuel, recycling or landfilling.

All MTB processes involve waste input and control, mechanical conditioning, biological treatment, and product conditioning. Waste input and control normally consists of manually removing oversized and hazardous materials. In the separation or splitting approach mechanical conditioning involves sorting of the inbound waste into biodegradable, recyclables and contaminant streams. Sorting is usually done with dry processes but it can also involve wet processes, such as floatation and hydro pulping. Depending on the quality and markets, the recylables are sold but paper fibres, textiles, rubber, plastics, and residual organics can also be used as RDF. The biological stage can either be aerobic composting or anaerobic digestion. The design and operation of the plants are basically the same as in SSO treatment.

The mixed or joint flux approach of treating the residual waste stream is essentially the same process used in handling waste that is not source-separated. In that respect it is the traditional method of managing the organic fraction of MSW and dates back to at least the start of the twentieth century. In some instances the waste is shredded before the composting process. Since the quality of the compost is lower than that of SSO compost and frequently does not meet regulatory standards for unrestricted use, many plants are designed to produce RDF using a composting technique that uses the heat released to dry the materials rather than digest the organic fraction. Metals and inerts are removed but paper fibres and plastics are part of the fuel. The caloric value of this fuel is relatively high (11 to 17 MJ/kg) and can be used as a substitute for fossil fuels in a wide range of applications, including power stations. The process also produces a low calorific value fraction that is normally landfilled. In the case where multiple levels of compost quality are allowed, the compost from a MTB can be used for one-time applications, such as site remediation, rather than as RDF or as landfill cover.

MBT technology is considered to be a proven technology and is rapidly becoming part of the integrated solid waste management system. It is particularly popular in Europe where there are some 70 MBT plants and over 20 MBT plant manufacturers. Italy, Germany, Austria, Switzerland, the Netherlands, and France have MBT facilities. Germany alone has some 29 MBT plants treating about 3 Mtpa to produce 1.4 Mtpa of RDF, complementing the 12 Mtpa of MSW processed in EFW plants.

A recent British study concluded that to meet future diversion objectives, will require MBT capacities of 3.5 Mtpa, 8 Mtpa and 11 Mtpa by 2010, 2013 and 2020, respectively.

Composting Process

MSW composting has been practised since the early 1900s in the Netherlands and a few other European countries; however, it was only on a limited scale. In recent years, it has become the main alternative treatment of the organic fraction of MSW in Europe and North America.

Composting is a natural process in which dead organic material is decomposed and returned to the soil. It is a self-heating, thermophilic, aerobic, biological process in which complex organic compounds are partially oxidized while releasing heat, water vapour, carbon dioxide, ammonia, and trace quantities of other gases. The non-mineralized component is humified to form a stable end product.

The application of stable, mature compost to agricultural crops has all of the benefits of direct application of sludges and food processing wastes but none of the potential odour and plant response problems. In particular, compost is an ideal material to combat the serious reduction in organic content of soils as a result of row cropping techniques, to alleviate erosion, provides nutrients to the plants, and is known to suppress a variety of plant diseases.

Composting is a biological process in that the active agents are microorganisms, such as bacteria, actinomycetes, and fungi. Fortunately, a wide spectrum of organisms is indigenous to MSW so that the main objective in successful composting becomes the provision of conditions conducive to microbial activity and rapid growth. The conditions include proper nutrition, and physical and chemical environments.

The organic waste fraction of MSW consists of a large number of simple and complex chemical compound, such as lipids, carbohydrates, proteins, amino acids, lignin, cellulose, and ash. One of the interesting aspects of the decomposition of this mixture is that different groups of nutritional and metabolic interacting microorganisms are required to decompose the mixture. Thus, the metabolic end products of one group of organisms becomes the nutrients of another group so that several groups are required to decompose complex waste into a stable product. However, the exact biochemical reactions resulting in the breakdown of organic wastes are very complex, and precise details of the biochemical changes are still lacking.

In a general sense the breakdown of proteins and carbohydrates includes the following pathways:

proteins ⇒ peptides ⇒ amino acids ⇒ ammonium compounds ⇒ bacterial protoplasm and atmospheric nitrogen or ammonia

carbohydrates ⇒ simple sugars ⇒ organic acids ⇒ CO_2 and bacterial protoplasm

The ability of a microbe to assimilate a nutrient source depends upon its capacity to synthesize the enzymes required to break down complex compounds into intermediate metabolites or into elements. Complex compounds require an extensive enzyme system and it may be supplied collectively by several groups of organisms. However, some complex compounds have molecular structures that can only be assimilated by a few groups of microorganisms, thus limiting the rate of decomposition of the waste. For example, materials consisting mainly of aromatic hydrocarbons, lignin, or cellulose are structurally more complex than highly proteinaceous materials, such as vegetables, meat scraps, etc., and therefore break down more slowly. As a result, the overall rate of composting is controlled to a significant extent by the nature and structure of the waste.

From an elemental chemical perspective, living organisms require large amounts of hydrogen, oxygen, carbon and nitrogen. Both hydrogen and oxygen represent a large percentage of cellular mass as water and as part of the cellular material. About 50% of the cellular mass consists of carbon and some 2 to 8% is nitrogen so that these two elements are known as macronutrients. In addition, phosphorous, sulfur, calcium and potassium are also required, albeit in much smaller quantities. Finally, several elements, mainly metals (cobalt, magnesium, manganese, iron, copper, molybdenum, etc), are needed in trace amounts and are called micronutrients.

Carbon is an essential macronutrient because it is a constituent of cell material and takes part in energy metabolism. Carbon is the major energy source for microorganisms and must be available in large quantities; however, not all the carbon contained in the waste is immediately available because some of it is bound in compounds that are resistant to biological attack. An example is the carbon in cellulose of newspaper where individual cellulose fibres are partially sheathed in lignin.

Nitrogen is also an essential macronutrient for growth and production of microbial cells. The amount of nitrogen needed per unit of carbon varies with the type and concentration of organism. Moulds, which are most active in the early stage of composting, require one part of nitrogen to thirty parts of carbon.

The carbon-to-nitrogen ratio (C/N) of organic waste is an important indicator of the compostability of a waste stream, and the practicality of composting as a means of treating that stream. It is generally agreed that a C/N ratio of between 30 and 40 to one is optimum for high-rate, aerobic decomposition. At a ratio less than 30/1, nitrogen is lost to the atmosphere in the form of ammonia; especially at high temperatures and pH. Under those conditions there is not enough carbon to provide the energy to convert all available nitrogen into protoplasm. On the other hand, excessively high C/N ratios cause a decline in the reproduction and growth of the microorganisms in proportion to the decrease of nitrogen in the substrate. This reduces the overall composting rate.

As mentioned, self-heating is one of the characteristics of the composting process. It is both an asset and a liability. Energy produced by biological oxidation of part of the carbon is partially used in metabolism but most of the energy is given off as heat. Since biomass is a poor conductor of heat, the temperature of the mass continues to increase until it reaches levels at which microorganisms are destroyed.

There are two threshold levels; the first one occurring around 45 ^{0}C causes the death or inactivation of mesophylic organisms and the proliferation of thermophilic ones. The upper threshold level is about 60 ^{0}C where growth becomes severely inhibited. Only a few species of thermophilic sporogenous bacteria show metabolic activity above 70 ^{0}C: *Bacillus stearothermophilus*, Bacillus subtilis, Clostridium sp., and non-spore forming bacteria, gram-negative, aerobic genus Thermus.

For high-rate composting the upper threshold temperatures must not be exceeded for long periods of time. However, it is beneficial to allow the process to exceed the level for some time to destroy thermosensitive human and plant pathogens. At other times the best performance is obtained when the process temperature is controlled between 50 and 60 ^{0}C.

Composting Process Design

The objective of the design of a high-rate composting process is to optimize and control the conditions for high microbial activity and growth. Carbon or nitrogen sources must be balanced to obtain a near optimum C/N ratio; for example, sewage sludge, which is generally high in nitrogen, can be co-composted with carbonic wastes. On the other hand, crop residues, wood shavings, wood chips, sawdust, or tree bark are excellent sources of carbon; however, they vary as to the availability of carbon.

As mentioned above, aside from a short sanitation period, the high-rate decomposition process requires a process temperature of 50 to 60 ^{0}C. Airflow in excess of the biological demand may be used to maintain the desired temperature. A temperature feedback control system, in which the biomass temperature is monitored and compared with the set point, is normally used to operate the air moving equipment for cooling. Since it takes approximately nine times more air to remove excess heat than to supply oxygen for microbial activity, one of the problems with aeration cooling is the excessive removal of moisture from the biomass. Therefore, moisture content monitoring is one of the process requirements and normally water or leachate must be added at some point in the process to maintain optimum conditions. The best time to add moisture is during mixing or agitation so that the moisture will be uniformly distributed.

Mature Compost

After completing the high-rate composting phase, the composted biomass must be stabilized and matured or cured before it can be used. Immature compost induces high microbial activity in soil after incorporation, potentially causing oxygen deficiency and a variety of indirect toxicity problems to plants. Furthermore, immature compost can cause severe odour problems during storage.

The curing phase takes longer than the high-rate phase and involves a host of microorganisms. Some composting systems produce green composts that require several months of curing in windrows; while other systems have a longer high-rate phase or operate at optimum conditions and therefore need less curing time.

Misconceptions and Limitations of the Composting Process

From every perspective composting is a process with a number of benefits and few disadvantages; however, there are several misconceptions and limitations associated with the composting process. One of the most significant misconceptions is that composting of MSW is an odourless process. This is simply not the case because not only does the inbound waste arrive in a semi-putrescible state but the process itself produces intermediate chemical compounds that are inherently odorous in nature. In addition, the development of anaerobic zones in the compost substrate due to poor management (low carbon/nitrogen ratio feedstock, poor temperature and/or aeration control, excessive moisture, and poor mixing) or inadequate design have frequently led to odour complaints in composting facilities. Remedying these causes reduces potential odour problems but do eliminate them.

In general, effluent gases from composting (and anaerobic digestion) include low molar mass pollutants such as ammonia, hydrogen sulphide, amines, mercaptans, aldehydes, ketones, alcohols, and/or volatile fatty acids at concentrations ranging from near 0 to 10 mg/m^3. For example, the unpleasant smell of sewage sludge is directly related to volatile fatty acid content. In biologically hydrolysed sewage sludge, about 60 - 70% of the soluble organic matter consists of volatile fatty acids. A sludge retention time of two to four days forms acetic acid while retention times of over six days favoured the generation of butyric acid. In the anaerobic degradation of soft-drink wastewater, about 60% of the glucose is converted to methane through butyrate.

Some of the problem compounds generated by the degradation of organic matter include acetaldehyde, acrolein, allyl disulphide, allyl mercaptan, ammonia, benzyl chloride, benzyl mercaptan, butyric acid, camphor, carbon disulphide, chlorine, diethylsulphide, dimethylamine, dimethylsulphide, mercaptan (methyl and ethyl), mercaptan (T-butyl and crotyl), formaldehyde, hydrogen sulphide, phenol, skatole, sulphur dioxide, and valeric acid.

Some odours work synergistically as they are carried away from the source, their combined effects may be more intense than if they existed alone in the environment. If there are multiple sources, the combination of more than one odourant results in a much more pronounced odour level than a single odour.

Once released to the atmosphere, volatile fatty acids are oxidized to carbon dioxide. The time lapse between the release of the volatile fatty acids and the oxidation reactions allows the volatile fatty acids to become problem odours, particularly when they are carried over large distances.

Odour Treatment

As mentioned above, the nature of biological processes makes it very difficult to completely eliminate odours. Therefore, proper plant and process design must include odour reduction, containment, and collection and treatment of the odorous air stream. There are a number of processes available to treat odours, including physical processes (adsorption, stack dispersion, odour masking and neutralization), chemical treatment (thermal oxidation, catalytic combustion, and ozonation or chlorination), and biological treatments(biofiltration and biotrickling).

The physical processes can be effective but have a high operating costs and usually transfer the pollutants from one medium to another; possibly creating another problem. Chemical treatment usually requires large capital expenditures. For composting operations, biological filtration has evolved as the method of choice because it is simple, relatively inexpensive, and reduces the odorants to carbon dioxide and water. When properly designed, biofilters work well, provided that they are operated correctly. Biofilter failures is usually due to operational problems, such as excessive loading rates, poor airflow distribution, insufficient or excessive moisture in the biofilter matrix or in the airstream, and inadequate dispersion of the treated gases.

Marketing

There is no shortage of beneficial use of compost. Agriculture is the largest potential user of compost and could easily absorb all the compost that can be produced in the country but farmers are generally reluctant to pay for compost, especially when it is made from MSW. Recent studies have shown that combining compost and fertilizer applications allows more efficient use of fertilizer by plants. This may increase the interest of agriculture in the use of compost.

High quality compost is also used for parks, sports fields, along roadsides, land reclamation, topping dressing of golf courses, and gardens with excellent results. Nevertheless, the development of a profitable market has proven to be difficult in North America and Europe. Many European communities give the compost away to farmers so that diversion from landfill is the only benefit to the community.

Acceptance of Composting in MSW Management

Composting of the organic fraction of MSW is widely accepted throughout the world. It is most commonly used in the European Union where some 2,500 Mtpa of biowastes are produced in agriculture (40%), garden and forestry (22%), sewage sludge (20%), food processing (10%), and municipal (8%). Composting and anaerobic digestion is used to treat about one third of the 50 Mtpa of recoverable municipal biowaste to produce about 9 Mtpa of compost. Germany is a strong proponent of composting and about 5 Mtpa of SSO waste is composted in more than 440 facilities.

The Composting Council of Canada 1998 survey of composting activities showed that there were 344 centralized composting facilities operating in Canada. 54 of these process food waste from the residential and ICI sectors, while 182 facilities process leaf and yard waste.

The United States is seeing growth in the number of composting facilities designed to handle SSO or mixed MSW as part of diversion programs. In 2002 there were 15 full-scale plants in operation with another ten under construction or being planned. Compared to Canada and the European Union, the United States is only starting to implement MSW composting.

Anaerobic Digestion (AD)

Like aerobic composting, anaerobic digestion or fermentation is also a natural process involving the biochemical degradation of organic material by micro-organisms. It is the dominant organic degradation process found in landfills and in bogs. Both processes produce a solid product that consists of inert organic and ligno-cellular materials and inorganic salts of nitrogen and phosphorus. The main difference in products is the gaseous stream; composting predominantly produces carbon dioxide, while AD produces a mixture of methane (typically 65-70%) and carbon dioxide (30-35%), known as biogas. Both processes also result in the generation of small fractions of other gaseous compounds.

AD is widely used on a residential level in developing countries, especially India and China, to produce energy for cooking and heating. In 1973 a US company[1] designed and extensively tested a simple AD system for homesite power generation using human, pet and livestock manures, and food waste. While there is no data on the commercial success of this system, AD has become increasingly important in manure management in agriculture as part of nutrient management programs. In 2003, there were 40 operating AD systems on dairy farms (29), swine farms (9), caged layer hens (1), and a duck farm (1) in the US (EPA AgSTAR Program). Because of the cost, only very large farms can afford the implementation of AD.

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[1] A Homesite Power unit: Methane Generator. Leslie M. Auerbach. Alternative Energy systems, Madison, CT. 06442 (1973)

AD Process and Technology

The AD process consists of four distinct sequential steps; namely

1. Hydrolysis or liquefaction: polymeric carbohydrates, lipids and proteins in the feedstock are hydrolysed into soluble organic monomers.

2. Acidogenesis - acidogenic bacteria convert the organic monomers into volatile fatty acid and alcohols.

3. Acetogenesis - acetogenic bacteria convert the fatty acids and alcohols into acetic acid, carbon dioxide and hydrogens.

4. Methanogenesis - acetic acid and hydrogen are converted in to methane and carbon dioxide by methanogenic microorganisms.

The AD process can be accomplished at three different temperatures. The cryophilic temperature (about 16 ^{O}C) occurs in landfills, the mesophilic temperature (about 35 ^{O}C) is normally found in in-vessel systems, and the thermophilic temperature (about 55 ^{O}C) is used in heated reactors.

Since the first two steps are biochemical in nature, they are accelerated by increasing the process temperature (approximately doubling the reaction rate for every 10^{O}C increase in temperature). The third step is equally temperature sensitive but microorganisms have a preferred temperature range beyond which they do not operate efficiently or at all. The fourth step works entirely within the above three temperature ranges because there are three distinct groups of methanogenic micoorganisms with life cycles in those ranges.

AD technology provides optimal operating conditions and control of the natural anaerobic digestion process in order to increase throughput and biogas yield. For example, if steps 1 and 2 occur too rapidly, the volatile fatty acids can overload the slower steps 2 and 4, resulting in an increased pH and inhibiting acetogenesis and methanogenesis. Hence, pH control is important.

AD technologies for MSW may be classified in terms of the amount of solids in initial process stream (wet or dry process), the operating temperature (mesophilic or thermophilic) and the number of digestion stages in separate reactors (single or two stages).

Not surprisingly, there are several definitions of dry and wet processes. One definition uses <15% total solids for dry processing and >15% total solid for wet processing. Another definition uses 20% total solids as the limiting concentration.

Due to the higher biochemical reaction rates and microbial activity, thermophilic plants have a lower hydraulic retention time than mesophylic plants. While there is a significant difference in reported retention times because of the differences in feedstock, design, and solids loading, one manufacturer has reported a retention time of ten days for its thermophylic plant and twenty days retention time for its mesophilic plant of equal capacity. Retention times from 15 to 30 days have been observed in thermophilic AD plants at loadings of 20 to 40% total solids. Mesophilic processes tend to produce biogas with a higher methane content than thermophilic processes.

In single-stage systems all four anaerobic steps occur in one reactor as a batch process. Some newer designs use multi-stage systems, usually two-stages, in which separate reactors are used for one or more steps of the anaerobic digestion process. By separating the steps, greater control can be implemented to obtain higher biogas yields with greater methane content. However, the capital and processing cost are also greater.

Biogas Production

Reported biogas generation yield vary significantly and can be a source of confusion if the process and the composition of the feedstock are not described in some detail. Aside from the different efficiencies of the technology, the biodegradable fraction of the organic material in the feedstock is an important factor (biodegradable fraction of newsprint is only about 0.22 on a volatile solids basis because of the high lignin content of newsprint, and 0.82 for food waste).

The most significant advantage of using AD is that it is a net energy producing process. It is generally accepted that in-house use of biogas is 20 to 50% of the total production, depending on the process and the process temperature. Some dry plants in Europe have an internal use of 20 to 30%, selling the balance to off-site users. Wet plants need about 50% of the energy produced for on-site use.

Examples of reported biogas production yields is given in the following table (BioCycle, Jan 2004.

PROCESS	FEEDSTOCK	BIOGAS YIELD (m^3/ton of waste)
single/two, wet, thermophilic	SSO/mixed	80 - 120
single, dry, thermophilic/mesophilic	SSO/yard trim	100
single, dry, thermophilic/mesophilic	mixed, SSO	80 - 160
single, wet, thermophilic/mesophilic	SSO	100 - 150
single, dry, thermophilic	SSO/yard trim	130
single, dry, thermophilic	SSO/paper	100 - 200

Acceptance of AD

Use of AD technology in waste water treatment plants dates back to the late 1800s and is now commonly found throughout the world. Serious interest in using the technology for

MSW probably started about three decades ago in Europe when locating of new landfill space became a major problem and energy cost had soared. In the US, Waste Management International constructed the first large-scale operation in 1978 to study the feasibility of AD to treat MSW for a seven years period. In France a dry-digestion, single-stage plant has been in operation since 1988 to handle the organic fraction of mixed MSW, while In Denmark a wet-digestion, two-stage plant has been operating since September 1991 to treat SSO.

While it is difficult to determine the current number of AD plants used to treat MSW, one report published in 2003 stated that 115 MSW-based AD plants were in operation throughout the world and that 40 were being built. Collectively the plants have a design capacity of 7 Mtpa. Apparently there were 70 AD MSW-based plants in operation in Europe in 2002 but by the end of 2003, some 21technology suppliers had at least 95 plants installed or under construction with a capacity ranging from 3000 to 210,000 t/yr (BioCycle, Jan 2004: 47-53). The six largest suppliers had sold eight or more plants, while many of the others had only one to three plants in operation or under construction. Presumably most of those are pilot or demonstration plants and area at this point relatively unproven technologies. Until recently most plants were designed to treat less than 20,000 t/yr but advances in design and experience in operating have resulted in the construction of more plants in the 40,000 t/y range.

Given the European experience, it can be concluded that AD to treat the organic fraction of MSW is a proven technology; however, not all of the processes on the market have a sufficient track record to be accepted as being proven processes.

Diversion Rate Using Biological Treatment

Since the organic fraction of MSW consists on average of about 70% (dry basis) volatile solids (Etobicoke waste averaged 72% but the sampling period was short and does not reflect seasonal effects), composting converts about 15 to 20% (wet basis) of the mass of the substrate into water, carbon dioxide, and trace amounts of other gases. In addition, the loss of moisture content of the feedstock results in another 30 to 35% (wet basis) mass loss. As a general rule it is assumed that the total mass reduction of wet feedstock is about 50%, depending on the degree of maturity and final moisture content of the compost.

It is not always appreciated that composting (and anaerobic digestion) of the organic fraction of MSW results in a significant residual waste stream, as well as a compost. The amount and quality of the residual waste depends greatly on the quality of the feedstock and is generally lowest for SSO collection programs and highest in mixed-waste collection programs. Despite excellent educational programs and participation rates, even SSO streams contain contaminants such as batteries, utensils, empty containers, medicine bottles, Qtips, etc. Some of these contaminants are readily removed in the feedstock preparation step; however, others end up in the composting process.

The amount of residue also depends on the end use of the compost and the quality standards set by the provincial governments. High quality compost destined for the horticultural market has to be cleaner than that used for general landscaping and site remediation.

Separation of most of the contaminants from the compost is achievable but at a relatively high cost. Screening with a small opening screen (e.g. 12 mm dia holes) is the most common approach to refining compost. This step is sometimes followed by destoning or air classification to remove pebbles and small pieces of glass. Each step produces a residual waste stream that has to be disposed of in some way.

Since compost produced from the residual waste stream of MSW is not likely to meet the metal and inert content standards for unrestricted use, it is assumed that the compost will be diverted to one-time application processes. Therefore, refining will be restricted to removing particles greater the 3/4" so that the amount of residue is assumed to be about 5% of the cured compost. It should be noted that if compost is used as RDF, it is not cleaned and no residue is generated at this stage.

In AD processes biogas production yield is the most important factor in determining the potential energy recovery and hence the economics of the system. It is much less important in determining the diversion rates because the unbiodegraded fraction becomes part of the solid product stream and is diverted as a compost.

The solids stream or digestate is first dewatered and then composted aerobically in a windrow system to cure and dry the solids. There is not a large reduction in dry matter during aerobic composting of the digestate because most of the volatile organics were consumed during the anaerobic process. The surplus liquid stream contains nitrogen in a readily available form and can be used in agriculture; however, it is often sent to a waste water treatment plant.

AD plants reduce the organic feedstock by about 45 to 65% on a mass basis, representing an approximate volume reduction of 60%. To translate this into a maximum MSW diversion rate requires that the biogas, solids and liquid streams are used in a beneficial manner.

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