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SEQUENTIAL BATCH ANAEROBIC COMPOSTING OF THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTE

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ABSTRACT

When kept free of toxic components, the biodegradable fraction of municipal solid waste (MSW) may be decomposed by aerobic or anaerobic composting and the residues either disposed of by land application or marketed as compost. Anaerobic composting is more economic because it effects similar conversion, does not require mixing or aeration, and produces the valuable energy product methane. This paper describes technical performance and systems analysis of a novel sequential batch anaerobic composting (SEBAC) process for treatment of high solids wastes that employs leachate management to provide organisms, moisture, and nutrients required for rapid conversion of MSW and removal of inhibitory fermentation products during start-up. The results of 19 trials with this system operated at 55°C and total residence times of 21 or 42 days exhibited about 50% conversion of organic matter with a methane yield of 0.2 m^3 kg^{-1} volatile solids. The process was reliable and stable. A systems analysis showed that tipping fees employing this process were in the $30 per ton range and that economics were highly sensitive to biodegradability of feedstock and residue use options; they were relatively insensitive to process kinetics and leachate recycle rate. This process can be applied to in-vessel or controlled landfill designs.

KEYWORDS

Anaerobic digestion; compost; municipal solid waste; leachbed; methane; sequential batch reactor.

INTRODUCTION

The biodegradable "natural" fraction of typical U.S. municipal solid waste makes up about 67% (dry wt. basis) of the total weight of this waste stream and is composed of approximately 41% paper, 18% yard wastes, and 8% food wastes (Franklin Associates, 1988). Factors which prevent direct land disposal of this fraction are: 1) contamination with non-natural toxic or refractory components; 2) unsightly appearance in its unprocessed form; 3) production of organic acids and odors during decomposition of the rapidly biodegradable fraction; and 4) attraction of pests and spread of disease. When separated from the undesired components (hazardous wastes, plastics, metals, glass, fabrics, etc.), shredded, and biologically treated to remove rapidly biodegradable components, the resulting compost product is not only suitable for land disposal, but significantly improves the water-retaining capacity of the receiving soil. This method of treatment provides the opportunity for integration of a major fraction of the waste stream into the natural stream for cycling of the elements in the biosphere.

The biological process applied to degradation of the rapidly biodegradable fraction of solid wastes is composting. Composting is normally considered to be an aerobic process accomplished either by mixing or forced aeration methods. Technically, however, the term composting addresses the fact that a biological stabilization process has occurred resulting in a product that has properties making it valuable as a soil amendment. The term is furthermore used most widely for treatment of feedstocks with a high solids content. We therefore support the use of the term composting in association with anaerobic digestion (De Baere et al., 1987) when applied to conversion of high solids feeds to compost and other products.

Although application of anaerobic composting to high solids feeds is less developed commercially than aerobic composting, it effects equivalent conversion at similar retention times and produces a compost of equivalent quality. Capital costs of anaerobic composting should be similar to those of in-vessel aerobic composting since front and end processing operations are similar and vessel designs are not substantially different (Legrand and Chynoweth, 1989; Legrand and Earle, 1990). The major advantages of anaerobic composting over aerobic composting are the lack of need for aeration or mixing and the production of a valuable fuel gas in addition to compost. For example, 100 tons (907 kg) of MSW will yield about $1,300 worth of methane (assuming $3 GJ^{-1}) and about $300 worth of compost (assuming $10 ton^{-1} compost). This indicates that the methane credit is significantly greater than that of compost and results in an economic advantage for anaerobic over aerobic composting of about $13 per ton MSW processed. Other advantages of anaerobic composting are maintenance of nitrogen in the reduced state and lack of odors associated with partially aerobic and partially anaerobic conditions common in aerobic composting.

SEQUENTIAL BATCH ANAEROBIC COMPOSTING (SEBAC)

Objective

The objective of this work was to develop a process for anaerobic composting that would overcome the limitations of other designs for processing of high solids feeds such as municipal solid waste. Accordingly the design goals were to minimize water addition, maximize inoculation, minimize solids handling, eliminate mixing, maximize conversion kinetics, and prevent development of instability during start-up and operation.

Process Description

The novel reactor design described here is of the multistage leachate recycle type and is referred to as the sequential batch anaerobic composting (SEBAC) reactor. Although it incorporates design features of other systems described (Barry et al., 1982; Ghosh, 1984; Hall et al., 1988; Jewell et al., 1983-1987; Rijkens, 1981, 1982; Smith et al., 1988), it has a unique combination of design and operating conditions. The SEBAC process shown in Figure 1 progresses through three stages for conversion of MSW to methane and requires at least two reactors, representing start-up and completion stages. In Stage 1 the putrescible fraction of MSW (mainly paper, yard waste, and food waste) is coarsely shredded (to about 10 cm),

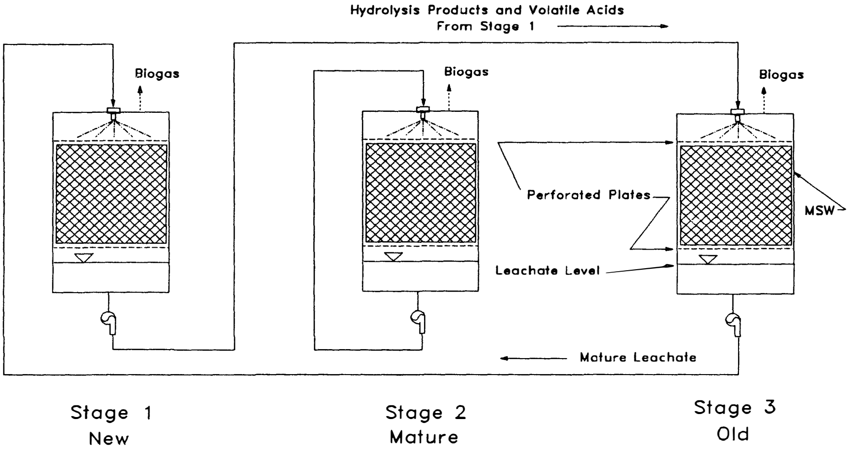

Fig. 1. Schematic of the sequential batch anaerobic composting (SEBAC) process.

placed into the reactor, and moistened and inoculated by recycling leachate from Stage 3. Leachate recycle also removes inhibitory organics produced in Stage 1 by depolymerization and fermentative reactions. In Stage 2 the fermentation is active and balanced and thus operated in the batch mode. Stage 3 allows for completed conversion of degradable particulates and also serves as an inoculum for start-up of Stage 1 and conversion of acids pumped out of Stage 1 via leachate recycle.

Operation and Performance

A pilot plant with three batch reactors (2.4 m high by 0.6 m ID) and all ancillary equipment, such as pumps, compressor, hot water heaters and gas meters, was constructed and operated at the University of Florida. The system was operated at 55°C to represent the natural temperature resulting from metabolic heat as determined by systems calculations presented below. Nineteen trials with two different sources of MSW and two different retention times were conducted and monitored. The MSW was collected fresh and processed by coarse shredding using a hammermill to a size range of 2-10 cm. Measurements included daily gas production and composition, daily concentration of volatile acids in leachate, and influent and effluent total and volatile solids. The operation and performance discussed elsewhere in detail (Chynoweth et al., 1990) are summarized below.

The composition of the two wastes streams used in this study is shown in Table 1. One, referenced Sumter, obtained from a composting facility had some recyclables removed but contained glass and plastic in addition to the desired paper and yard waste. The other, referenced Levy, contained principally paper with small amounts of yard waste.

The first reactor was started up by mixing equal volumes of MSW and effluent from a mesophilic slurry anaerobic digester receiving a blend of MSW and primary sludge. The second run was started up by recycling leachate from the bottom of the first reactor to the top of a new batch of MSW. All subsequent runs were started by recycle of leachate between the old and new runs, Stages 3 and 1, respectively. The kinetics progressively increased for the first four runs while subsequent runs exhibited similar and the most rapid kinetics. We think that a possible explanation for increased kinetics for the first few runs is a reflection of buildup of organisms responsible for the rate-limiting reactions; however, no data were obtained to substantiate this.

TABLE 1 Comparison of MSW Composition from Sumter and Levy Counties

	Sumter*		Levy**	
	Mean	Range	Mean	Range
Total Solids	71.1	56.5 - 80.2	65.6	62.0 - 72.5
Vol. Solids	81.3	77.0 - 88.4	92.5	89.5 - 95.3
Paper (%)	47.3	22.0 - 65.2	91.5	85.0 - 98.5
Cardboard (%)	10.9	0.0 - 24.6	4.1	0.4 - 7.0
Plastic (%)	9.7	4.0 - 21.4	0.3	0.0 - 0.9
Yard Waste (%)	5.9	0.0 - 33.0	1.9	0.0 - 8.4
Misc. (%)	22.6	11.5 - 67.7	0.0	0.0 - 7.4

* MSW from Sumter County comes from a recycling facility, where ferrous metal, aluminium and some cardboard boxes and plastic bottles (PET) are removed from the MSW before it is shredded with a hammermill.

** MSW from Levy County was sorted by hand. The organic fraction used as feedstock for the digesters contained primarily paper, yard and food waste.

A performance profile for a typical 42-day run is shown in Figure 2. During the initial part of Stage 1 (first 14 days), volatile acids accumulated to over 3000 mg L^{-1} and methane production was minimal. Accumulative methane yield and methane gas content rapidly increased after 5 days, indicating development of a balanced methane fermentation. During this stage, acids were carried via leachate recycle to another reactor operating in Stage 3 where they were converted to methane and carbon dioxide. Most of the methane was produced in Stage 1. The rate of methane production leveled off in Stage 2. Methane in Stage 3 was produced in part from residual conversion of MSW and in part from volatile acids carried over from another reactor in the process of start-up. PH was in the range of 7.5-8.0 which is abnormally high for anaerobic digestion; no reason could be determined for this trend.

Operation and performance data for all runs are summarized in Table 2. In general performance was stable in all runs and similar for the different feedstocks. Conversion and associated methane yields were slightly lower for the 21-day runs (7 days per stage) compared to 42-day runs (14 days per stage). For the 42-day runs conducted with only Sumter MSW, a mean methane yield of 0.19 m^3 kg^{-1} VS was achieved with a range 0.18 - 0.22. A mean volatile solids reduction of 49.7% was achieved with a range of 46.6 - 52.4. For the 21-day runs with Sumter MSW, a mean methane yield of 0.16 m^3 kg^{-1} VS was achieved with a range of 0.13 - 0.19. A mean volatile solids reduction of 36% was achieved with a range of 21 - 44. For the 21-day runs with Levy MSW a mean methane yield of 0.19 m^3 kg^{-1} VS was achieved with a range of 0.18 - 0.21. Volatile solids reductions for the two runs evaluated were 37 and 45%. Biochemical methane potential data shown in Figure 3 suggest that greater than 90% of the anaerobically degradable organic matter is converted by this process, suggesting that conditions were suitable for conversion, including accessibility of particles to microbial activity.

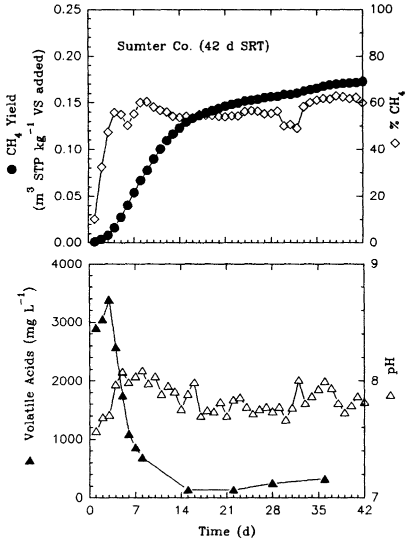

Fig. 2. Performance data from a typical 42-day run of SEBAC receiving Sumter Co. MSW.

TABLE 2 Summary of Performance of all SEBAC Runs*

Parameter	Sumter (42 day) Mean	Sumter (42 day) Range	Sumter (21 day) Mean	Sumter (21 day) Range	Levy (21 day) Mean	Levy (21 day) Range
Methane Yield (m^3 kg^{-1} VS)	0.19	0.18-0.22	0.16	0.13-0.19	0.19	0.17-0.22
Met. Rt. (vvd)	0.61	0.56-0.64	1.02	0.84-1.27	1.06	1.00-1.13
VS Redn. (%)	49.7	48.9-52.4	36.0	21.1-44.4	40.6	36.7-44.6

*Loading was about 3.2 kg VS m^{-3} d^{-1} for 42-day runs and 6.4 kg VS m^{-3} d^{-1} for 21-day runs; temperature was 55°C; leachbed bulk density was 280 kg m^{-3}; methane gas content was 55-60% except during first 5 days of start-up.

SYSTEMS AND ECONOMIC ANALYSIS

Introduction

A mathematical model of a refuse biogasification facility was designed using Lotus^R 1-2-3 spreadsheet software to evaluate performance sensitivity to kinetics, materials and energy balances, and economics. It includes modules describing feed processing, anaerobic digestion, gas use, residue processing, energy balance, and levelized cost calculations. A detailed description of this model and assumptions used is presented elsewhere (Chynoweth et al., 1990).

In this model, the user specifies the general configuration of the MSW biogasification system as well as the essential inputs. Choices are provided between landfilling the residue or refining it into compost, and between marketing medium Btu gas or using the biogas to generate power with an internal combustion engine and sell that power to the grid. Inputs include MSW quality and quantity; gas sales price; and selection of base year for levelized cost. The user also enters values for conversion variables such as solids retention time (SRT), digester temperature, and percentage methane in the biogas produced. These inputs are used in the process modules which include preprocessing, biogasification feed input, anaerobic digestion assumptions, conversion, gas processing, gas blending, process energy, cost, and levelized cost.

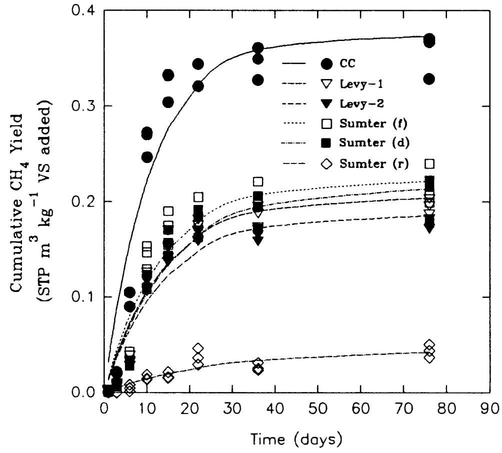

Fig. 3. Biochemical methane potential of SEBAC MSW feedstocks and residue. CC is cellulose control, Levy-1 and Levy-2 are feedstocks from Levy Co. Sumter Co. samples are fresh, (f), dried, (d), and SEBAC residue, (r).

Kinetics

The kinetics of Stage 2 of these runs was predictable and the first-order rate constant for volatile solids conversion ranged from 0.043 to 0.061 day^{-1}. Taking into consideration Stages 1 and 3, which were more variable and usually higher, an overall mean rate constant of 0.08 day^{-1} was observed and used for other analyses. For biodegradability calculations we used a biodegradable volatile solids (BVS) to VS ratio of 0.50 which was similar to conversions observed at long retention times and biochemical methane potential assays. The other consideration in applying kinetics is the bulk density developed in the reactor. In our reactors a bulk density of 280 g TS L^{-1} was typical. For systems calculations we assumed a bulk density of 291 because of higher compaction expected in taller tanks. Using the above kinetic constant, it was determined that over 90% of the biodegradable volatile solids would be converted in 35 days which became the selected retention time for simulations. Finally, it was determined that a minimum of five reactors should be employed in a commercial system to minimize fluctuations in gas production to less than 20%.

Heating Analysis

While supplemental heating may be required to initially bring MSW and added leachate up to the nominal operating temperature of 55°C, biological heat production is expected to contribute to maintaining this temperature. In a large system, as described in the following section on system base case economics, the tanks may actually require cooling during the period of rapid degradation.

Using summertime design temperatures for Gainesville, Florida, a simulation of heat losses was performed for the full-scale system described in Table 4 using parameters listed in Table 3. No loss of heat is attributed to the recirculation of leachate since, in fact, we expect the leachate to be used to provide any net heating or cooling requirement. Assuming no lag time, an initial loaded tank temperature of 55°C, and a simple first-order kinetic model we can calculate the net heat loss rate, Q_{net}, as the sum of the rates of conductive heat loss, Q_c, sensible heat loss in the biogas, Q_s, latent heat loss in the biogas, Q_l, and biological heat loss (input), Q_b. Recent studies of biological heat production in anaerobic digestion using flow micro-calorimetry (Samson et al., 1988), allow a conservative estimate of the biological heat yield of 533 kJ kg^{-1} VS destroyed. While the conductive heat loss remains constant over the retention period the other losses are proportional to biogas production rate. As shown in the plot of the contributions of the various heat losses in Figure 4, there is an overall net gain in heat for the first 14 days of the retention period. Thus, without supplemental cooling, the reactor contents can be expected to heat up during this initial stage.

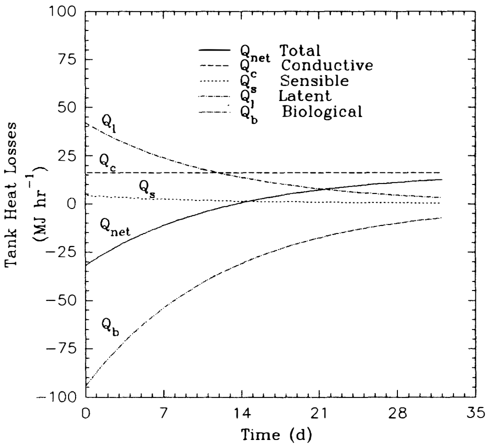

Fig. 4. Simulated heat losses in full-scale SEBAC tank composting MSW.

Previous work (Chen and Hashimoto, 1981) discounted this biological heat contribution in their analysis of continuous slurry systems, due to its small value relative to the large heat requirement of continuously heating slurry influent to digester operating temperature. The high solids nature of the SEBAC reactor contents results in a lower specific heat allowing smaller heat inputs to effect larger temperature increases when compared to more dilute slurry systems. High temperatures (> 60°C) can be expected to inhibit the bioprocess in a manner similar to aerobic composting. While no indication of self-heating has been experienced in the pilot-scale system, low surface to volume ratios in larger tanks are expected to result in some self-heating in full-scale systems.

TABLE 3 Design Parameters Used in Heating Analysis

Parameter	Value	Unit
Tank diameter	7.6	m
Tank height	11.6	m
Air temperature	35	°C
Ground temperature	22.2	°C
Tank insulation thermal resistance	1.07	°K hr m^2 kJ^{-1}
Tank bottom thermal resistance	0.15	°K hr m^2 kJ^{-1}
Dry biogas density (@55 °C, 1 atm)	1.07	kg m^{-3}
Biogas specific heat (@55 °C)	1.5	J g^{-1} °K^{-1}
Water content of saturated biogas	0.113	kg H_2O kg^{-1} dry gas
Latent heat of evaporation	2253	J g^{-1} H_2O
Biological heat yield	533	kJ kg^{-1} VS destroyed

Base Case Economics

The base case parameters are summarized in Table 4. Note that the SRT is 32 days, with three days allotted for reactor turnovers, resulting in a total cycle time of 35 days. The resulting distribution of costs and credits is illustrated in Figure 5. The costs expressed in $ per ton (907 kg) of MSW processed are displayed in the left half of the bar charts, broken down by subprocess. These are comprehensive levelized costs, in other words, they include debt service and all operating costs. The total cost amounts to $47.4 per ton processed MSW in 1990 dollars or $1,422 per day for this 35-tpd facility. Biogasification accounts for approximately 50% of this cost, while MSW preprocessing and residue processing comprise about 20% and 30%, respectively. Note that if there were no biogasification, i.e., this would be a conventional recycling facility, there would be more solid residue to landfill and the cost of residue disposal would increase substantially.

The revenues used to pay these costs are shown in the right half of the bar diagram. The tipping fee is $33.4 per ton MSW processed and covers 70% of the costs. Gas sales provide the remaining revenue. It has been conservatively assumed that no net income is derived from the sale of recyclables or compost. Under these and other assumptions listed in Table 5, a simple materials recovery facility would require $43.5 per ton, an aerobic in-vessel composting facility would require $47.4 per ton, and direct landfilling would cost $40 per ton. Note that 15% of the MSW is recycled, 25% is gasified, 57% is converted to compost, and 20% is landfilled. This total comes to more than 100% due to the addition of dilution liquid. The latter is unnecessary if the MSW is extremely moist or biodegradable. The percentage gasified would also increase if a more degradable feedstock (such as MSW and yard waste) were used.

TABLE 4 Summary of Base Case Parameters

Mass Balance:	Capacity = 35.3 tpd (ton*/day) MSW (7 days/week; = 49.4 tpd, 5 days/week) 15% by mass removed in preprocessing and recycled 30 tpd MSW-derived feed 7 tpd dilution liquid added 8 (dry) tpd converted to gas 27 tpd of filtercake @ 50% TS
Feed:	76.4% TS 79.7% VS (of TS) 50.0% BVS (of VS) Bulk density = 289 kg m^{-3} 1.2 g COD/g VS
Conversion:	Temperature = 55°C k = 0.08 day^{-1} VS conversion efficiency = 46.1% Methane yield = 0.19 m^3 kg^{-1} VS Methane prodn. rate (vvd) = 1.39 Biogas prodn. rate (vvd) = 2.53 VS Loading Rate = 7.2 kg VS m^{-3} d^{-1} SRT = 32 days (plus 3-day turnover)
Byproducts:	Biogas: 5830 m^3 d^{-1} at 55% Methane Sold as medium Btu gas at $3 per GJ Solid residue screened to product compost 7 tpd of rejects landfilled 20 tpd of compost sold at $0/ton (given away)
Economic Inputs:	Landfill tipping fee = $40/ton Electricity purchase = $0.06/kWh Electricity sale = $0.04/kWh Cost escalator = 6%/year Service factor = 90% (10% downtime or 5 weeks/year) Current dollar return to debt (= interest rate) = 8.1%

*1 ton = 907 kg

Sensitivity Analyses

A series of sensitivity analyses were performed to determine the effects of operating parameters on per-unit cost in dollars per ton MSW. Parameters evaluated include facility size, biodegradability of feed, leachate recycle rate, reaction rate, solid residue processing options and value of byproducts. For each analysis, the base case was used and only one parameter was varied to examine its impact on cost. Four examples of the results of these analyses are shown in Figure 5. The results show that economics are significantly influenced by facility size, ratio of BVS to VS, compost value, and energy product value; they are relatively insensitive to reaction rate (at a constant retention time), digester retention time, and leachate recycle rate.

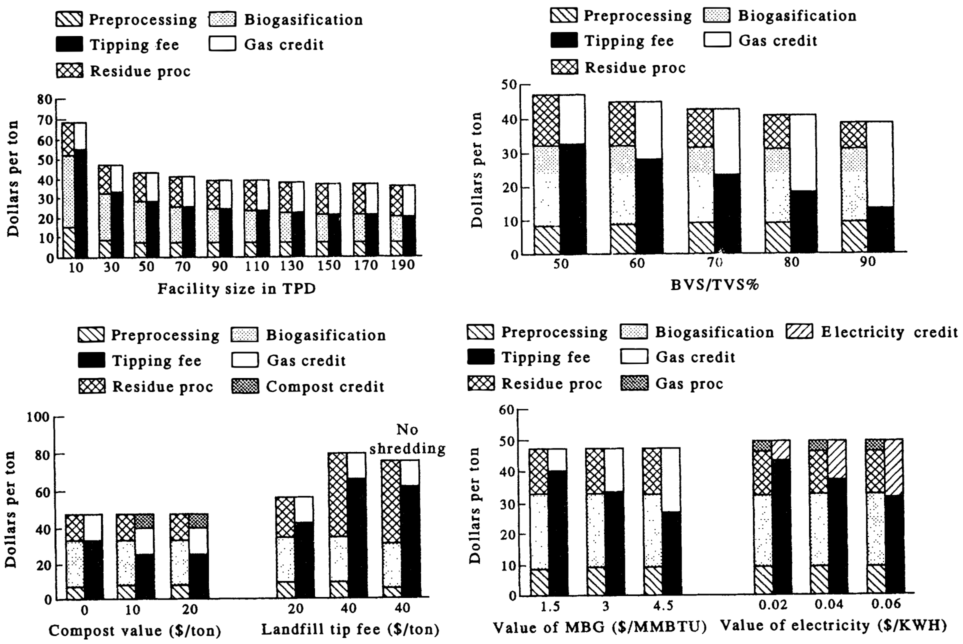

Fig. 5. Levelized costs and credits as a function of facility size, feed biodegradability, solid residue processing options, and biogas processing options.

DISCUSSION

The results of this pilot-scale study show that the sequential batch anaerobic composting (SEBAC) process is effective for conversion of the biodegradable fraction of municipal solid waste to methane and carbon dioxide. At an operating temperature of 55°C, mean methane yields of 0.19 and 0.16 $m^3\ kg^{-1}$ VS and corresponding volatile solids reductions of 50% and 45% were obtained at residence times of 42 and 21 days, respectively. The loading rates corresponding to the 42 and 21 days experiments were approximately 3.2 and 6.4 kg VS $m^{-3}\ d^{-1}$, respectively, which is influenced by the bulk density in the digester bed of MSW. It is anticipated that this density may increase, resulting in a higher loading rate. It is not known what effect this will have on hydraulic conductivity of leachate or reactor kinetics. Based on these results the residence time for complete conversion of biodegradables would be between 21 and 42 days. The conversion efficiencies were similar to those reported by others with similar feeds (Barry et al. 1982; De Baere et al. 1987; Ghosh, 1984) and are largely a function of the feed composition rather than the process. As indicated in Table 1 the composition of feed varied considerably but was composed primarily of paper.

Start-up of the process was rapid. For the first four trials, the kinetics of each trial increased, indicating a buildup of active microorganisms. After these initial four trials, each following trial developed an active methane fermentation within a few days. Following initiation of the run by recycle of leachate from the Stage 3, volatile acids accumulated in the leachate to levels in the range of 3000-4000 mg L^{-1}. These were removed and converted to methane via leachate recycle back to the Stage 3. After the start-up was complete (7 or 14 days), the methane content increased from 0 to 55% and the system entered Stage 2 where it was recycled upon itself in order to maintain moist conditions. We were not able to conduct studies to optimize leachate recycle strategies and think that further research on this is needed. Despite the variation in feed composition, there was no broad range of variation in the performance parameters, suggesting that the process is very stable.

The systems analysis showed that the minimum economical size (based on a tipping fee of $40/ton) for the SEBAC process is 30 tpd MSW or larger. Economics were sensitive to the biodegradability of the feedstock. This could be maximized by up-front sorting to restrict plastics and other non-biodegradable materials. Retention time (21 days versus 42 days) had very little impact on costs, thus reaction rate and reactor size are relatively unimportant. For retention times between 19 days and 59 days costs ranged within five percent of optimum. This may be attributed to the fact that the reactor is a relatively small proportion of the total process cost. Although the influence of leachate recycle rate on kinetics was not evaluated this parameter may be worth investigation since it may improve performance but has minimal influence on economics. Refining the solid residue into a compost was economically superior to landfilling, not because of the possible revenue from compost sales, but because most of the material is diverted from the landfill. This option will be influenced by the quality of the compost and will require front-end processing to prevent input of toxic materials in the feedstock that would contaminate the compost residues. Process heat requirements had minimal influence on economics. This is related to the low water content of the feedstock and use of well insulated reactors.

The design of SEBAC has several advantages over other designs for anaerobic digestion of MSW and other high solids feeds. The process is very stable and has a built-in mechanism for prevention of imbalance, i.e. removal of volatile organic acids from their site of formation via leachate and transfer to an active methanogenic reactor. Another advantage is the lack of solids handling (such as mixing) during the digestion process; solids handling is limited to filling and emptying. Finally, it is a very simple system to design and operate; the system could be implemented in bunkers or landfill cells.

Further Development

The sequential batch anaerobic composting process appears to be technically and economically feasible at its current state of development, however, there remain uncertainties with respect to the design of the next scale and there is potential for further improvements by optimizing several operational parameters and evaluating other feedstocks such as yard waste, crop residues, and other leachable feedstocks. Research is needed on hydraulic conductivity of feedstocks at various bulk densities and different stages of decomposition. There is room for optimization of leachate management, e.g. the optimum time and rate for recycle and effect of bed flooding. Integration of the methane enrichment concept (Hayes et al., 1988, Jewell et al., 1983-1987) should be evaluated. This concept involves air stripping of leachate to remove carbon dioxide from the system and enrich the gas methane content. Process design may be varied to include controlled landfill cells, horizontal bunkers, and traditional in-vessel tanks. Finally, a direct comparison of this process to aerobic composting should be made on the basis of conversion efficiency versus processing time, process reliability, energy requirements, and compost quality.

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