0273-2289/93/3940—0071$03.40

Anaerobic Bioconversion of Municipal Solid Wastes Using a Novel High-Solids Reactor Design

Maximum Organic Loading Rate and Comparison with Low-Solids Reactor Systems

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ABSTRACT

Novel, laboratory-scale, high-solids reactors operated under mesophilic conditions were used to study the anaerobic fermentation of processed municipal solid waste (MSW) to methane. Product gas rate data were determined for organic loading rates ranging from 2.99–18.46 g of volatile solids (VS) per liter (L) per day (d). The data represent the anaerobic fermentation at high-solids levels within the reactor of 21-32%, while feeding a refuse-derived fuel (RDF)/MSW feedstock supplemented with a vitamin/mineral/nutrient solution. The average biogas yield was 0.59 L biogas/g VS added to the reactor system/d. The average methane composition of the biogas produced was 57.2%. The data indicate a linear relationship of increasing total biogas production with increasing organic loading rate to the process. The maximum organic loading rate obtainable with high-solids anaerobic digestion is in the range of 18–20 g VS/L·d to obtain 80% or greater bioconversion for the RDF/MSW feedstock. This loading rate is approximately four to six times greater than that which can be obtained with comparable low-solids anaerobic bioreactor technology.

Index Entries: Anaerobic digestion; MSW; high solids; low solids; organic loading rate.

INTRODUCTION

An estimated 250 million tons of municipal solid wastes (MSW) are discarded each year in the United States, representing about 1.5–2.0 quads of energy (*1*). The bulk of this material is either landfilled or burned. Because of public concern about hazardous emissions from combustion processes and the decreasing number of landfill sites, interest in alternative waste-disposal processes has increased. Although the composition of MSW varies with respect to location, season, and time of day, the major components are biodegradable, and in the form of cellulose (paper), lignocellulosics (sawdust, wood, grass clippings, and cardboard), and food wastes (*2–4*). Mechanical processing of the MSW to remove recyclable materials, such as glass and metals, decreases the heterogeneity and increases the cellulose content (*5*).

Anaerobic bioconversion of organic feedstocks, such as MSW, has the potential of producing both considerable energy (methane) and a high-grade fertilizer/soil conditioner. However, several key issues must be overcome before the methane produced is economically competitive with conventional sources of natural gas. Because the value of the methane produced is relatively low, the anaerobic process must be rather simple in design, require little energy to operate, and have high gas production rates. The conversion process must also result in near complete digestion to maximize energy production and residue value.

The most common use of anaerobic digestion is in the disposal of municipal sewage wastes (*6–8*). This organic waste stream is relatively dilute, and the overall effect of sewage treatment is to convert a water pollution problem into a solid-waste-disposal problem. The primary purpose of anaerobic digestion for treating sewage wastes is to reduce the organic content, volume, and odor potential of the sludge, and to reduced the concentration of pathogenic microorganisms (*6–9*). However, because of the high level of water present, the anaerobic digestion process is carried out in conventional low-solids, stirred-tank reactor systems. These systems are large and require substantial energy inputs for heating and mixing.

In preliminary economic evaluations of anaerobic digestion processes for the production of fuel gas from solid wastes, reactor capital costs have been identified as an important cost factor in part because of the large reactor volumes required for conventional low-solids digestion processes. If the reactor volume could be reduced significantly and power use maintained or decreased, the economics of the anaerobic digestion process would benefit greatly. Increasing the solids concentration within the reactor would be particularly beneficial in this respect, because a decreased reactor volume is possible while the same solids loading rate and retention time are maintained. However, high-solids slurries are very viscous and resemble solid materials more closely than typical fluids. Therefore, conventional mixers, such as those employed in continuous stirred-tank reactor (CSTR) systems, do not ensure homogeneity within the reactor, and problems develop in providing adequate dispersion of substrate, intermediates, and microorganisms while minimizing power requirements.

High-solids anaerobic fermentations are commonly found in the landfill disposal of MSW. However, landfill high-solids anaerobic bioconversion is very slow because of the lack of process control (*10*). High-solids anaerobic bioreactor technology development has employed nonmixed (or packed) batch-operated reactors (generally with liquid recycle [*11–17*]) as well as mixed or partially mixed reactor designs (*18–21*). However, previous mixed systems have had disadvantages in that either a significant level of recycle is required for inoculation of the added feed (plug flow design) or the level of solids within the reactor is limited by the mixing system (i.e., gas recirculation or hybrid impeller designs).

A novel approach to high-solids mixing that ensures effective dispersion of substrate, microbial catalyst, and intermediates at truly high-solids concentrations (0–100% solids) has been developed (*22*). This reactor system is significantly different from those previously reported in the literature and allows the study of the high-solids anaerobic process at the laboratory scale. This high-solids reactor design employs an agitator with a horizontal axis, and was designed, fabricated, and tested in studies for the high-solids anaerobic bioconversion of processed MSW. The laboratory-scale reactor system has allowed us to establish many of the important process parameters for high-solids anaerobic bioconversion of refuse-derived fuel (RDF)/MSW (*22,23*), including the optimum agitator for effective mixing and reduced horsepower usage, the minimum mixing requirements (≤ 1 rpm for this particular agitator), and the maximum sludge solids level (35–40% solids) for active microbial bioconversion. The device is currently operated in semicontinuous (daily batch feeding) mode, but may be modified for continuous operation.

The objective of this study was to determine the maximum organic loading rate for the high-solids process using a processed MSW feedstock amended with a defined nutrient supplement. These results are then compared to results established in previous research studies in the scientific literature.

MATERIALS AND METHODS

Feedstock

The MSW feedstock used in this study for comparison purposes consisted of processed and densified MSW (also referred to as RDF) obtained from Future Fuels, Inc., Thief River Falls, MN. This material represents the drier paper and packaging fraction of MSW, and was described previously (*24*). This feedstock was subjected to size reduction appropriate for the bench-scale fermentation studies to be performed. Feedstock comminution was accomplished with an industrial-scale knife mill equipped with a 1/8-in round hole rejection screen. The milled feedstock was stored in plastic-lined 55-gal drums at room temperature until use.

Previous research on the anaerobic bioconversion of MSW feedstocks identified the need for nutrient supplementation (25). Therefore, a nutrient solution (as previously described [25]) was added to adjust the moisture content of the feedstock as well as to ensure sufficient nutrients for robust biological activity.

High-Solids Reactors

The laboratory-scale high-solids reactors used in this study were described previously (22); each consists of a cylindrical glass vessel positioned with a horizontal axis and capped at each end. The agitator shaft runs horizontally along the axis of the cylinder, and mixing is obtained with a rod-type agitator (tines) attached to the shaft at 90° angles with opposing orientation. Shaft rotation is provided by a low-speed, high-torque, hydraulic motor (Staffa, Inc., England). The glass vessel was modified with several ports including two 3/4-in ports for liquid introduction and gas removal, and a 2-in ball valve (Harrington Plastics, Denver, CO) used for dry feed introduction and effluent removal.

The four high-solids reactors used in this study were maintained at 37°C in a temperature-controlled warm room (Fig. 1). The reactors were operated semicontinuously in that feed was introduced daily through the separate addition of dry-milled feed and a liquid nutrient solution. Sludge was removed from the reactor on a biweekly basis and stored at 4°C until analysis.

Biochemical Methane Potential (BMP) Assays

The BMP assays were performed as previously described (26) to determine the maximum anaerobic biodegradation yields for the MSW feedstock by the anaerobic consortium over an extended period of incubation (90 d). This value serves as a reference for comparison to the theoretical yields for each feedstock (as determined from feedstock chemical oxygen-demand values) as well as to the anaerobic bioconversion performance utilizing the high-solids fermentation system. The BMP assays were conducted in 155-mL serum bottles incubated at 37°C and mixed using an orbital shaker. Biogas production was measured using a pressure transducer equipped with a 22-gage needle for penetration into and subsequent overpressure release from the serum bottle stopper. Following the conclusion of the 90-d incubation, the composition of the biogas was determined.

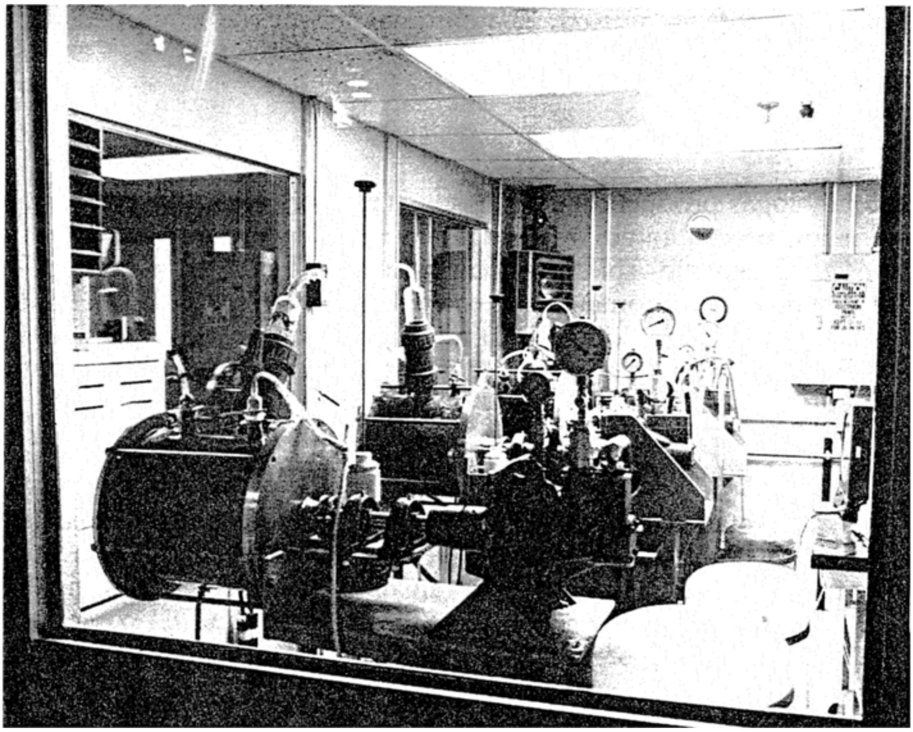


Fig. 1. Four bench-scale high-solids reactors operating within a temperature-controlled warm room. The cylindrical glass vessels have a total vol of 20 L, and mixing is accomplished by individual hydraulic motor assemblies.

Feedstock/Digester Effluent Analysis

The solids concentrations of both the feedstock and digester effluent samples were determined using 1-g aluminum weigh tins. A 20- to 30-g sample was loaded into preweighed tins and dried for 48 h at 45–50°C. The dried sample was then cooled to room temperature in a laboratory desiccator and weighed using a Sartorius balance (Model 1684MB). The percent total solids was calculated on a weight/weight basis, and the percent volatile solids and ash was determined by combustion of the dried samples at 550°C for 3 h in a laboratory-scale furnace.

The MSW feedstock was analyzed for carbon oxygen demand (COD) content as previously described (27). The COD assay employed the microdetermination method using commercially available "twist tube" assay vials (Bioscience, Inc., Bethlehem, PA).

Levels of volatile organic acids (C_2-C_5 iso- and normal-acids) were determined by gas-liquid chromatography (GLC). A Hewlett-Packard Model 5840A gas chromatograph equipped with a flame ionization detector, a Model 7672A autosampler, and a Model 5840A integrator (all from

Hewlett-Packard) were used. The chromatograph was equipped with a glass column packed with Supelco 60/80, Carbopack C/0.3%, Carbowax 20M/0.1% H_3PO_4 for separations.

Gas Analysis

Total biogas production in high-solids reactor systems was measured daily using precalibrated wet tip gas meters (Rebel Point Wet Tip Gas Meter Co., Nashville, TN). The composition of the biogas produced was determined by gas chromatography as previously described (*28*). For this analysis, a Gow-Mac (Model 550) gas chromatograph equipped with a Porapak Q column and a thermal conductivity detector with integrating recorder were used.

Theoretical Methane Yield

The theoretical methane yield for the MSW feedstock was calculated as previously described (*26*) from the feedstock COD content. The ratio of the actual methane yield for a given anaerobic fermentation to the theoretical methane yield calculated from the feedstock COD content is a direct reflection of the organic carbon conversion of the substrate added.

RESULTS

The high-solids fermentation data presented are a result of research conducted over a 2½-yr period in which changes in the feed rate (referred to as the organic loading rate and given in units of grams of volatile solids added per liter of active sludge per day) required a 1- to 2-mo period of adjustment to attain stable fermentation performance. A stable fermentation is defined here as resulting in relatively consistent gas production rates (within 5% variation), and sludge pH and volatile fatty acid pools of >7.0 and 10 m*M* (cumulative), respectively. Once at a stable fermentation rate, data were taken for a 1- to 2-mo period in which parameters of total biogas production, biogas methane composition, effluent solids levels, effluent residual volatile fatty acids, and pH were routinely measured. The data for the 1- to 2-mo collection period were then averaged and are presented as follows.

Product gas rate data are shown in Fig. 2 for organic loading rates ranging from 2.99–18.46 g VS/L·d. The data represent the anaerobic fermentation at high-solids levels within the reactor of 21–32% fed a RDF/MSW feedstock supplemented with a vitamin/mineral/nutrient solution. No significant difference in anaerobic bioconversion was demonstrated as a result of changes in the sludge solids level from 21–32%, which is consistent with previous studies (*23*). The average methane composition of the biogas produced was 57.2%. The dashed line repre-

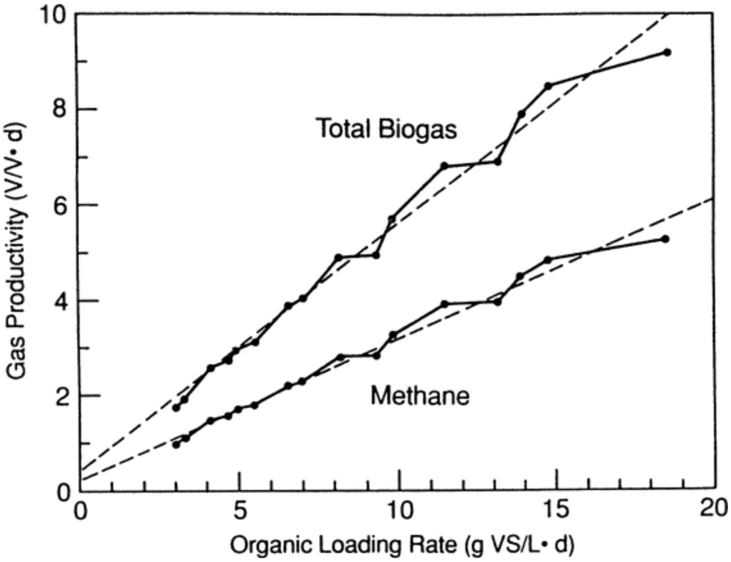
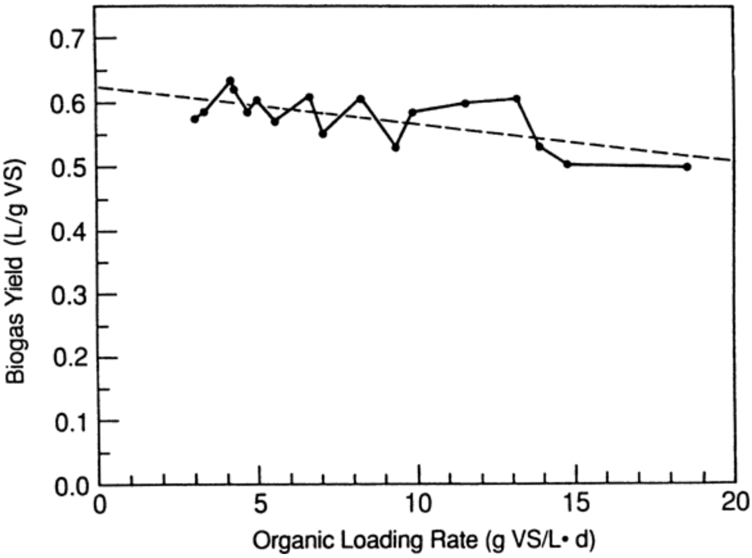


Fig. 2. Comparison of total biogas and methane productivity with changes in the organic loading rate. These data represent the average of daily gas production data for a period >2 mo. The variation in averaged data was <5%. The dashed line represents the linear regression of the data.

sents the linear regression of the data points. The slope of the line is a function of the level of feedstock degradation, as well as the composition of the feedstock. The composition of methane in the biogas is a function of the mean oxidation state of the feedstock as previously described (29). For RDF/MSW, this mean oxidation state is between carbohydrates and proteins.

The total biogas yield over the range of organic loading rates tested is depicted in Fig. 3. The dashed line represents a linear regression of the data and indicates a decreasing yield with increased organic loading to the digestion system. However, the trend toward a reduced yield over the organic loading range tested is slight. A comparison of the total biogas production at the various organic loading rates in relation to the total biogas that may theoretically be produced if the retention time were exceedingly long (in other words, if the microbial consortium had an extended incubation time with which to degrade the feedstock, as determined by data from the BMP_{90} assay) is shown in Fig. 4 as a percent of the BMP_{90} biogas production. The data follow the same trends as in Fig. 3 with the majority of the organic loading rates resulting in 80–100% of the BMP_{90} biological conversion. The BMP_{90} conversion respresents approx 72% of the theoretical conversion possible as determined from the feedstock (RDF/MSW) COD content. However, the conversion at the 18.46 g VS/L·d loading rate is approx 80% of the BMP_{90} biogas, and it is estimated that organic loading rates greater than this will result in even lower levels



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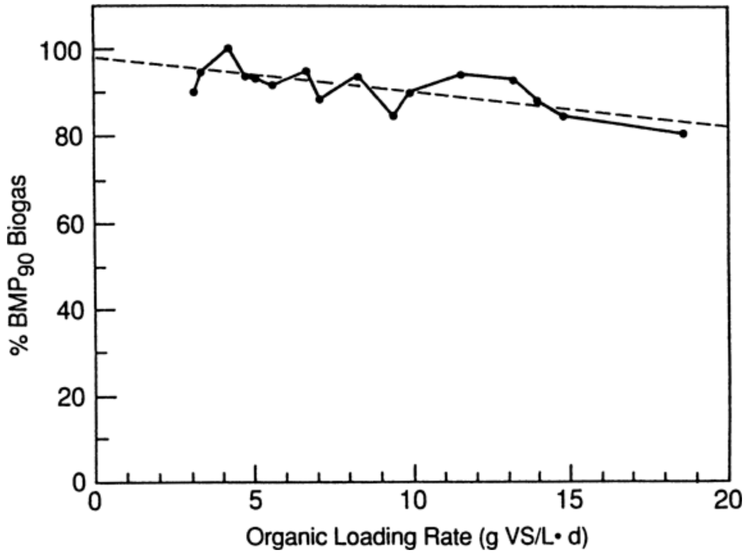

Fig. 4. Comparison of the percent BMP_{90} biogas production with changes in the organic loading rate. The dashed line represents the linear regression of the data.

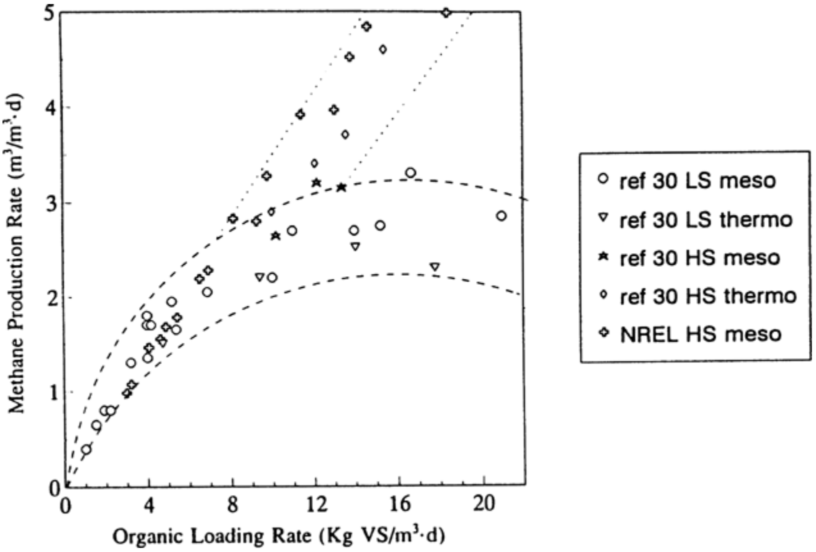

Fig. 5. Comparison of the methane production rate with changes in the organic loading rate for the NREL high-solids system and the summarized European efforts. Data points include anaerobic digestion systems operated at low solids (LS), high solids (HS), and mesophilically (meso) as well as thermophilically (thermo).

of bioconversion. Therefore, the ceiling for the organic loading rate for high-solids anaerobic bioconversion of RDF/MSW is estimated to be approx 18–20 g VS/L·d. Further increases in the organic loading rate to the process will result in reduced bioconversion, which in turn will result in a reduced methane yield and, possibly more importantly, greater residue bulk (through higher VS content), which may support undesirable biological activity when used as a soil amendment. The quality of the residue is extremely important in determining the market for this product or the lack thereof.

If the data generated from this study are compared with those developed from research studies on anaerobic bioconversion of MSW wastes in Europe as summarized by Cecchi et al. (*30*), shown in Fig. 5, the data indicate two clear trends. The trend for low-solids systems is depicted by a curve that demonstrates a loss in bioconversion expressed in this figure as methane production rate over increased organic loadings. However, in two sets of data for high-solids systems (both the NREL high-solids process operated at mesophilic temperatures as well as the Dranco thermophilic high-solids process), the methane production rate appears linear over the organic loading rate range. This trend is also evident in Fig. 6, which compares the European data with regard to specific methane yield.

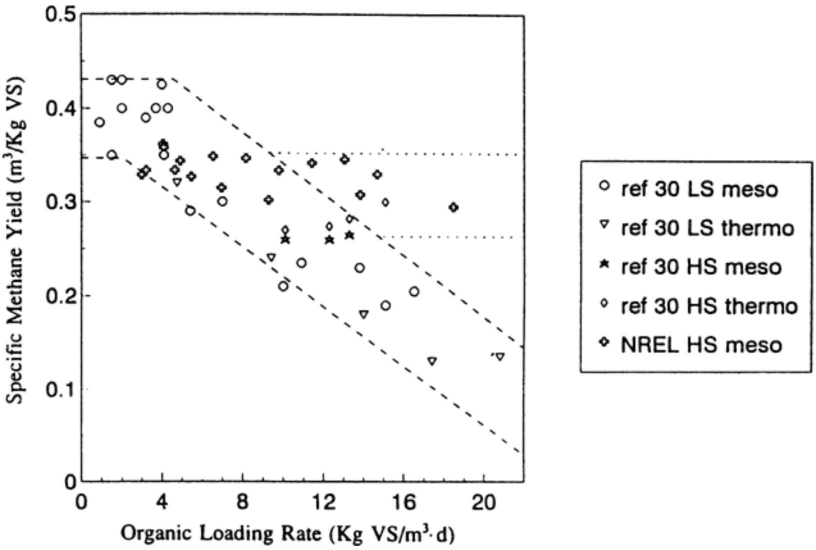

Fig. 6. Comparison of the specific methane yield with changes in the organic loading rate for the NREL high-solids system and the summarized European efforts.

Again as described above, the methane yield for a given feedstock is a function of the feedstock composition as well as extent of bioconversion. When the feedstock composition remains constant, this yield is a direct reflection of the extent of bioconversion.

One explanation for the enhanced conversion efficency obtained with high-solids systems at high organic loading rates relates to the retention time of feedstock solids within the bioconversion system. Since the anaerobic bioconversion process is operated in the most economical method (i.e., no addition of hydrolytic enzymes or microbes to enhance the rate-limiting step of polymer hydrolysis [*31–33*]), the process is generally recognized to require long contact times (retention times) in order for the hydrolytic microbes to break down polymer feedstocks fully. Therefore, the feedstock solids retention time is a crucial parameter to obtaining near complete anaerobic bioconversion of polymeric feedstocks, such as MSW. This relationship was evaluated previously (*34*). From this study, and under optimal nutrient levels, the anaerobic bioconversion process required a retention time of at least 20 d to convert 80% of the cellulose in the feedstock. If we consider a low-solids system fed a feedstock that is 80% volatile solids at 8% total solids, the highest organic loading rate that may be obtained before reducing the retention time below 20 d is 3.2 g VS/L·d. This is consistent with the European data in Fig. 6, which depicts a drop in anaerobic bioconversion at organic loading rates >4–5 g VS/L·d However, because of the lack of process water required for feed introduction to the reactor, the high-solids reactor design allows for high organic loading rates while maintaining retention times in excess of 20 d (retention time for 18.46 g VS/L·d loading rate was 25 d).

DISCUSSION

In summary, the maximum organic loading rate obtainable with the NREL high-solids anaerobic digestion system operated mesophilically is in the range of 18–20 g VS/L·d for the RDF/MSW feedstock. This loading rate is approximately four to six times greater than that which may be obtained with comparable low-solids anaerobic bioreactor technology. However, it is important to note that the maximum organic loading rate is for the most part (especially with high-solids systems) a function of the feedstock composition. Where polymer hydrolysis is the rate-limiting step (which is the case with MSW feedstocks), the organic loading rate may be limited by the minimum retention time of the system, which in turn dictates the polymer conversion extent. However, for more readily biodegradable feedstocks in which the rate-limiting step may not be the hydrolysis of polymers, the organic loading rate may be significantly higher and may instead be a function of the growth rate of the microbial consortium. In both cases, the organic loading rate may be increased artificially by supplementing the digestion system with either hydrolytic enzymes or microbes, although for economy of operation this is rarely practiced.

ACKNOWLEDGMENT

This work was funded by the Waste Management Program of the US Department of Energy.

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