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Demonstration-Scale Evaluation of a Novel High-Solids Anaerobic Digestion Process for Converting Organic Wastes to Fuel Gas and Compost

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ABSTRACT

Early evaluations of the bioconversion potential for combined wastes such as tuna sludge and sorted municipal solid waste (MSW) were conducted at laboratory scale and compared conventional low-solids, stirred-tank anaerobic systems with the novel, high-solids anaerobic digester (HSAD) design. Enhanced feedstock conversion rates and yields were determined for the HSAD system. In addition, the HSAD system demonstrated superior resiliency to process failure. Utilizing relatively dry feedstocks, the HSAD system is approximately one-tenth the size of conventional low-solids systems. In addition, the HSAD system is capable of organic loading rates (OLRs) on the order of 20–25 g volatile solids per liter digester volume per d (gVS/L/d), roughly 4–5 times those of conventional systems.

Current efforts involve developing a demonstration-scale (pilot-scale) HSAD system. A two-ton/d plant has been constructed in Stanton, CA and is currently in the commissioning/startup phase. The purposes of the project are to verify laboratory- and intermediate-scale process performance; test the performance of large-scale prototype mechanical systems; demonstrate the long-term reliability of the process; and generate the process and economic data required for the design, financing, and construction of full-scale commercial systems. This study presents conformational fermentation data obtained at intermediate-scale and a snapshot of the pilot-scale project.

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Index Entries: High solids; anaerobic digestion; biogas; cogeneration; pilot-scale.

INTRODUCTION

The anaerobic digestion of lignocellulosic materials such as municipal solid waste (MSW) and biomass, is limited by the hydrolysis rate *(1,2)*. The primary biodegradable polymer in MSW and biomass—cellulose—may be shielded by lignin, a relatively inert, polyphenylpropane, three-dimensional polymer *(3)*, or by hemicellulose *(4)*. This complex structure dictates that natural biodegradation occurs on a scale of months or years, rather than hours or days. Such slow rates of polymer degradation require long retention times, large reactor volumes (for conventional low-solids systems); thus, they result in high capital costs for large-scale application.

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.

In preliminary economic evaluations of anaerobic digestion processes for producing fuel gas from solid wastes, reactor capital costs have been identified as important factors. 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 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.

Early research on anaerobic digestion conducted at the National Renewable Energy Laboratory (NREL) under funding from the United States Department of Energy focused on enhancing the fundamental understanding of the HSAD process. A novel horizontal-shaft bioreactor was designed for laboratory studies of the process. These laboratory-scale digesters were used to study a wide variety of process parameters, including the most effective agitator designs and best procedures for adapting the anaerobic microbial consortia to high-solids levels *(5)*, the nutrient requirements for optimum anaerobic conversion rates *(6)*, the maximum solids levels and minimum mixing requirements *(7)*, the maximum process organic-loading rate *(8)*, and the minimum retention time for effective high-solids conversion *(9)*. Laboratory-scale digesters were used to study the levels of extracellular hydrolytic enzymes in the anaerobic digestion process and their

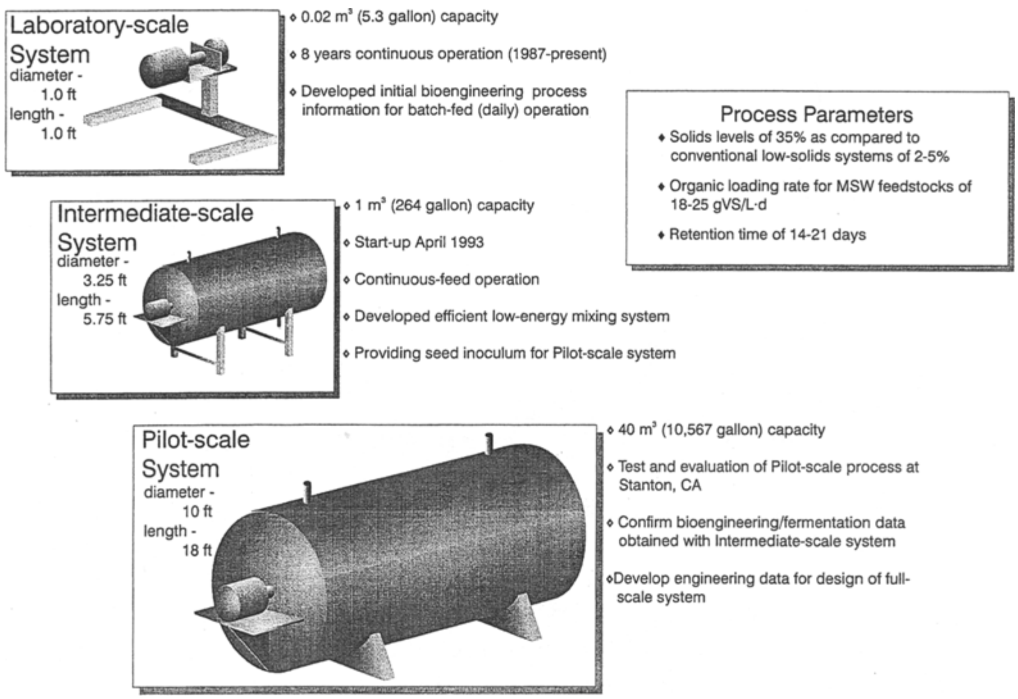

Fig. 1. Scale-up efforts detailing laboratory-, intermediate-, and pilot-scale system dimensions and operational parameters.

effects on conversion rates *(10–14)* and the effects of total solids on microbial populations *(15)*. Various organic feed stocks including sorted MSW feedstocks *(16)*, the blending of sorted MSW and food-processing wastes *(17,18)*, various agricultural residues *(19)*, dewatered sewage sludges *(20,21)*, and sewage-derived fat, oil, and grease *(22)*, were evaluated with the laboratory-scale high-solids digester. Finally, the laboratory-scale digesters were used to study the apparent horsepower requirements for mixing at various solids levels *(23)*, as well as the application of high-solids anaerobic residues as a soil amendment *(24)*.

After establishing a firm understanding of the important process parameters that affect the high-solids digestion process, research focus shifted to issues of bioreactor scale-up and the benefits of high-solids operation on commercial-scale system capital and operating costs. Independent review of the HSAD process confirmed the economic advantages of the process application *(25)*, but only laboratory-scale fermentation data were available. These data also formed the basis for a computer-modeling approach to simulating the commercial-scale costs (and benefits) of applying HSAD technology to industrial-waste disposal *(26)*. A step-wise approach to scale-up of the novel horizontal-shaft agitator bioreactor (United States Statutory Invention Record #H1149, March, 1993) is depicted in Fig. 1 and follows 40- to 50-fold scaling increments. Research efforts now focus on confirming high-solids anaerobic digestion process performance determined previously using laboratory-scale bioreactors at intermediate- and pilot-scales to enhance confidence in economic model simulations for commercial-scale technology application. The current work summarizes intermediate-scale HSAD fermentation data and outlines pilot-scale efforts.

METHODS

Intermediate-Scale High-Solids Digestion System

The unique bioreactor design allows for a plug-flow movement of feed solids during the digestion process with zonal mixing to release entrained gas pockets and provide inoculation of feedstock entering the digester. Slow-speed, tine-blade agitation enhances microbial film formation in the digester. A 1000-L (1 m^3) intermediate-scale high-solids digestion system was fabricated by Interpro (Golden, CO). The digester was approx 1.0 m (3.25 ft) in diameter, 1.75 m (5.75 ft) long, and constructed from 304 stainless steel. The vessel was fabricated with five ports for feed introduction, effluent sludge removal, product biogas removal, a 2.5 psi graphite rupture disk, and an inspection window. Feedstocks were blended with a small commercial dough mixer and continuously fed to the intermediate-scale digester with an adjustable-speed screw feeder. The digester was mounted on a 2268-kg (5000-lb) platform scale with digital readout to monitor sludge level on a weight basis. Process-effluent sludge was removed from the digester with a pneumatic-operated pinch valve at the opposite end of the digester from the feed port. Digester biogas head pressure was maintained at approx 0.5 psig with a water-filled gas bubbler. Biogas was measured with both a standard wet-gas meter and a mass-flow meter with totalizer. Digester temperature was maintained at 55°C with an electric heating blanket. Digester temperature was regulated with an internal thermocouple probe and a temperature controller. The horizontal-tine agitator assembly was designed to be similar to laboratory-scale high-solids systems and employed a hydraulic motor with a 16:1 gear reducer to maintain a constant 1 rpm shaft speed. The data acquisition and control system (DACS) used a GE Fanuc model 90/30 programmable logic controller (PLC) and Wonderware software (Intouch, Irvine, CA) on a PC-based server as the man machine interface (MMI). Daily data reports were logged in Excel spreadsheet files for retrieval and data analysis.

Feedstock

The blended feedstock for the intermediate-scale digestion studies was similar to that used in laboratory-scale studies. Analysis of the tuna sludge and MSW used during all experimental studies is shown in Table 1.

Table 1
Feedstock Characteristics

Parameter	Feedstock	
	MSW (RDF)	Tuna sludge
Total solids (%)	96.8 ± 0.2	24.9 ± 1.6
Volatile solids (as % of TS)	88.8 ± 0.5	94.2 ± 0.9
Ash (as % of TS)	11.2 ± 0.5	5.8 ± 0.9
Chemical oxygen demand (g COD/g wet wt)	1.21 ± 0.11	0.35 ± 0.03
pH	—	5.3
Volatile fatty acids (C2–C5, m*M*)	—	117.9 ± 14.2
Free ammonia (g/L)	—	0.78 ± 0.08

Analytical Analysis

Analysis of feedstock and process-residue samples for total solids, volatile solids, ash, pH, free ammonia, chemical oxygen demand (COD), volatile fatty acids, and biogas composition were as previously described *(21,27)*.

RESULTS

Intermediate-Scale HSAD Development

Design, fabrication, and start-up of the intermediate-scale, high-solids digestion system is documented elsewhere *(28,29)*. HSAD performance data obtained during a 2-y effort that employed the intermediate-scale digestion system are described in Table 2. Data obtained for process organic-loading rates (OLRs) of 18 and 20 gVS/L/d were taken at three retention times and may not fully represent steady-state data. However, the average anaerobic bioconversion (as determined by feedstock COD reduction) is in the low 80% range. This level of conversion at OLRs of 4–20 gVS/L/d confirms previous data determined for laboratory-scale HSAD studies that used the blended tuna sludge and MSW feedstock *(30)*. High conversion rates may also be attributed to longer solids retention times (i.e., 16 d at 20 gVS/L/d loading), which are a consequence of a lower water content in the feedstock.

Pilot-Scale HSAD Development

Confirmation of laboratory-scale high-solids data at intermediate-scale further enhanced confidence in the process economics to pursue pilot-scale system development. In addition, equipment selection for material-handling issues that relate to continuous-feed addition, process monitoring, data collection, and effluent removal increased confidence in the ability to effectively design larger-scale systems. Following com-

Table 2
Intermediate-Scale High-Solids Digester Performance at Various OLRs

Organic loading rate (gVS/L/d)	4	8	10	12	14	16	18	20
Biogas production (L/L/d)	3.19 ± 0.31	5.62 ± 0.52	8.10 ± 0.52	9.88 ± 0.90	10.51 ± 1.10	11.50 ± 1.09	12.61 ± 0.99	12.94 ± 1.46
Methane content (%)	57.7 ± 3.4	63.4 ± 3.1	57.5 ± 1.2	56.0 ± 1.4	58.8 ± 1.7	60.1 ± 2.0	59.7 ± 2.3	59.1 ± 2.8
Methane production (L/L/d)	1.84 ± 0.18	3.56 ± 0.33	4.66 ± 0.36	5.53 ± 0.50	6.18 ± 0.69	6.91 ± 0.81	7.53 ± 0.88	7.65 ± 1.10
COD loading (g COD/L/d)	5.9	11.7	14.6	17.5	20.4	23.3	26.2	29.2
% Bioconversion[a]	85.5 ± 8.5	83.9 ± 7.7	87.7 ± 6.7	86.8 ± 7.9	83.1 ± 7.2	81.2 ± 8.1	78.6 ± 6.9	71.4 ± 9.1
Sludge total solids (%)	26.3 ± 1.3	26.7 ± 1.8	26.2 ± 2.1	26.5 ± 1.9	26.8 ± 3.2	27.2 ± 2.9	27.8 ± 3.1	28.2 ± 4.1
Sludge pH	7.4 ± 1.1	7.4 ± 1.8	7.3 ± 1.6	7.3 ± 1.1	7.3 ± 1.8	7.3 ± 1.4	7.2 ± 2.1	7.2 ± 1.9
Sludge VFAs (C2–C5, mM)	23.1	32.1	29.1	39.1	44.4	59.7	54.7	59.2
Sludge ammonia (g/L)	1.3	1.3	1.3	1.2	1.3	1.3	1.3	1.2

[a] The percent anaerobic bioconversion was determined from the COD loading to the process using the relationship of 1 g COD is equivalent to 0.35 L of methane. All methane production values were first corrected for STP prior to calculating the percent bioconversion.

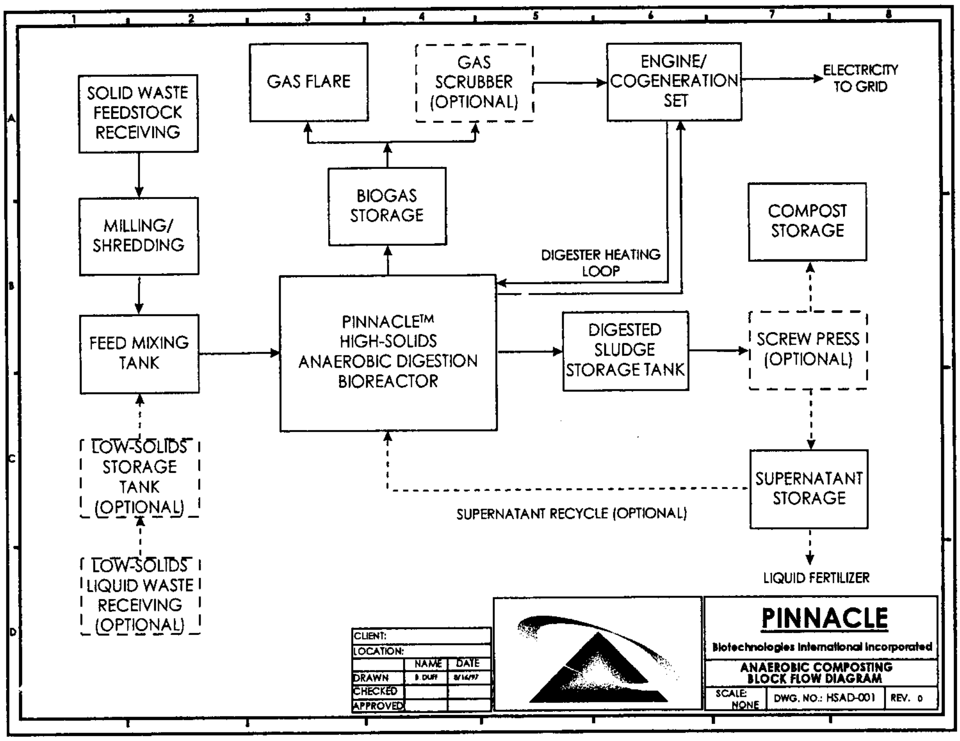

Fig. 2. Block-flow diagram of the pilot-scale HSAD process installed at Stanton, CA and used to confirm smaller-scale fermentation system performance for MSW and tuna sludge feedstocks.

petitive procurement practices, a contract was awarded (December, 1994) to Bioengineering Resources (Fayetteville, AR) to design, fabricate, install, and operate a 2 ton/d anaerobic digestion pilot system for treating a combined feedstock of MSW and tuna sludge. Collaborators on the project included Black and Veatch (Kansas City, MO) for engineering work and Envirex (Waukesha, WI) for design and fabrication of the digester system. Stanton, CA was selected for the pilot plant site to locate the system close to the MSW sorting facility of the project's partner, CR&R. This site is also close to the source of tuna processing sludge, provided by Tri Union International (Terminal Island, CA). Local site permitting assistance was provided by The Planning Center (Newport Beach, CA), and SCEC (Orange, CA).

Early design engineering work consisted of a collaboration by Black & Veatch, Bioengineering Resources, and developers at NREL. The block-flow design for the pilot-scale system is shown in Fig. 2. The design, fabrication, installation, and permitting stages are complete. Commissioning of equipment and start-up (including inoculation of the pilot-scale digester) are underway.

DISCUSSION

Fermentation performance data for applying high-solids anaerobic digestion of MSW, biomass, and food processing wastes were determined to be very successful at laboratory- and intermediate-scale. Economic projections that used the data developed to date also demonstrate that HSAD provides a cost-effective alternative to normal routes for disposal of organic wastes such as landfilling, aerobic composting, and incineration. Early assessments of high-solids anaerobic digestion performance that used the novel, horizontally mixed design developed at NREL indicate substantial product-yield improvements over competing designs *(31)*. Comparison of the HSAD system with conventional, low-solids designs and even with alternative high-solids designs has demonstrated a 10 to 65% greater yield in methane production. This may be attributed to the design of the system, which encourages both biofilm production and plug-flow operation. However, pilot-scale fermentation performance data are necessary to further refine the projected economics for commercial-scale applications (these kinetic data form the basis for computer-model-simulating programs). Operating the pilot-scale system also allows the unique set of equipment chosen for integration to be verified; thereby addressing important solids-handling issues that pertain to applying this technology to a wide variety of solid organic feedstocks. The successful commercialization of the HSAD process would provide many community and industrial leaders with an alternative, environmentally responsible, method for recycling organic wastes.

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