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Anaerobic Digestion of Municipal Solid Waste in a Nonmixed Solids Concentrating Digestor

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ABSTRACT

This paper reports on the performance and characteristics of a 4.5 m^3 nonmixed, vertical flow Experimental anaerobic digestion Test Unit (ETU) treating refuse-derived fuel (RDF) and primary sludge. It was operated at 35°C and a loading rate of 3.2 kg VS/m^3/d. Three tests involving chemical nutrients addition or effluent supernatant recycle were completed. Hydraulic retention times were 16, 18, and 19 d, respectively. Methane yields ranged from 0.24 to 0.28 m^3/kg VS fed, which were 10–20% higher than that from a continuously-stirred tank reactor. Methane compositions were around 58%. Solids distribution, pH and volatile fatty acids (VFA) concentrations profiles, and the ability of microbial communities at various depths to utilize acetate and other VFAs were used to characterize the ETU.

Index Entries: RDF; MSW; anaerobic digestion; nutrients recycle; methane.

INTRODUCTION

The developed nations of the world are increasingly concerned about increased production of municipal solid waste (MSW) and its associated environmental impact. Concerns over air pollution and diminishing land availability are putting pressures on the now widely-used practices of

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mass burning and landfilling (1). A large fraction of MSW is biodegradable and can be efficiently converted to fuel gas, as had been demonstrated in various processes (2,3). A Community Waste Research Facility at the Walt Disney World Resort Complex in Orlando, FL was created under the overall mission of developing systems to provide a secure supply of energy from community resources and offer cost-effective waste disposal and wastewater treatment alternatives to the community. It has, as its main feature, an experimental test unit (ETU), a 4.5 m^3 Solids Concentrating anaerobic digestor that has been successfully operated for the digestion of biomass and sludge blends (4).

Digestion of refuse-derived fuel (RDF) in the ETU started in 1987. To date, three tests have been completed. Chemical nutrients were added during the first two tests (5). The objectives of the third test were to determine the technical feasibility of nutrients conservation through effluent supernatant recycle and the consequent performance and characteristics of the ETU. In addition, better ways to take profile samples were needed. During the first two tests, profile samples were collected by opening valves on side ports of the ETU. Plugging of valves and dewatering of samples were major problems with this practice, causing concerns in the validity of the samples.

MATERIALS AND METHODS

Facility Description

The ETU facilities include the digestor (ETU), a feed storage tank, a weigh tank, an effluent storage tank, a primary sludge storage tank, a gas storage tank, piping that connect these tanks and a number of pumps, a control panel area that houses indicators and controls for the various pumps, and a trailer that serves as a lab and office (Fig. 1). A screw press with a 10 cm auger was made for dewatering effluent. All tanks except the effluent storage tank are insulated with polyurethane and can be cooled by circulating well water of about 21°C through their jackets. Details of the ETU facilities have been presented elsewhere (6).

Digestor

The ETU is a cylindrical digestor of 4.5 m^3 working vol with an internal diameter of 1.37 m and a height to diameter ratio of 2:1. External piping arrangement was made such that the ETU could be fed through the top or bottom. Side ports of 5 cm diameter at 30 cm vertical intervals allow sampling and recirculation from various depths. During the period covered by this paper, the ETU was fed once a day through the top and operated in a down-flow mode. A spray nozzle at the end of the feed line distributed the feed uniformly over the digestor culture. Internal baffle rings of 15.2 cm width at 60 cm vertical intervals prevented short-circuiting of the feed.

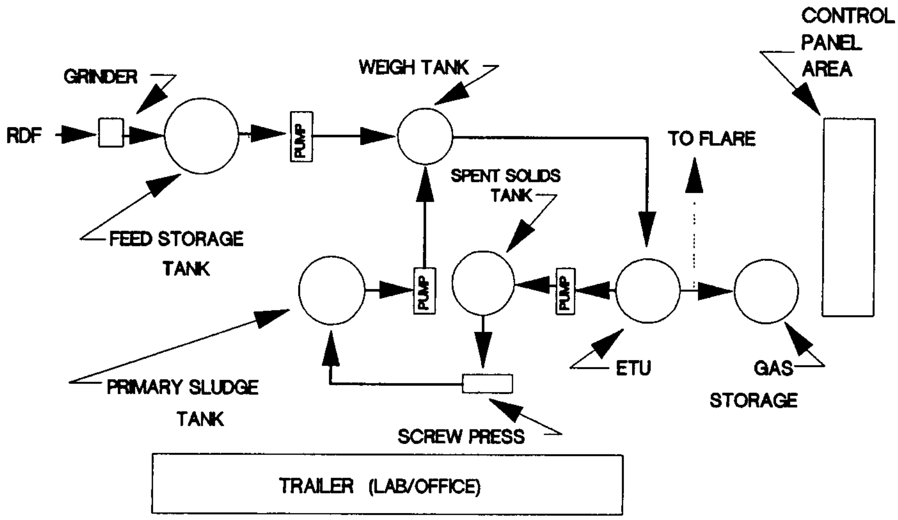

Fig. 1. Schematic layout of the ETU facility.

The temperature of the digestor was controlled at about 35 °C by a thermocouple located at about 1 m height. An effluent storage tank provided effluent storage of up to 1 wk. Gas production from the ETU was continuously accumulated with a Rockwell International gas meter that was calibrated for 15.5 °C base temperature.

A 50 L, continuously-stirred digestor (CSD), fed once a day, was operated as a control for the ETU. Feed was introduced through a 1.9 cm diameter opening on the top and effluent withdrawn through an opening of the same size at the bottom. Mixing was done with motor-driven paddles. Gas produced was directed to a sealed manometer containing acidified and saturated salt solution. When a fixed volume of gas was accumulated, an optical sensor triggered a counter, then a solenoid valve to release the gas. Gas production was determined by the number of counts registered.

Feedstock

Both digestors received a feed consisting of RDF and sludge from a nearby wastewater treatment plant. RDF is the combustible part of MSW, consisting mostly of paper and plastics. RDF used in this work did not include food and yard wastes and was obtained from National Ecology (Baltimore, MD). This source was chosen for its ability to deliver a 0 × 1.27 cm size RDF (*6*). The RDF was shipped to the ETU site in fiber-lined drums and stored at about 16 °C in a refrigerated trailer.

Primary sludge was pumped once a week from the primary clarifier of the Reedy Creek Utility Company's wastewater treatment plant at Lake Buena Vista, FL. It was allowed to settle in a primary sludge tank to a total solid (TS) concentration of about 4%. The concentrated sludge was used to make up the feed.

Feed was prepared once a week. To facilitate pumping, the RDF was wetted and ground with an Urshell Mill grinder through a cutter head with 0.32 cm openings. Sludge was added to make up a slurry such that the volatile solids (VS) ratio between the RDF and primary sludge was 15:1, which was determined earlier to represent a typical community waste. Fresh water and raw sewage along with chemicals were added during the first test to make up a feed of 8% TS. The feed used during the second test contained about 45% by weight of effluent supernatant. During test 3, a screw press was used to dewater effluent, and supernatant from the press contributed about 85% by weight of the feed used. No chemical was added. The feed was kept at 21°C in a weigh tank prior to use. Load cells on this tank gave accurate measurement of the quantity fed. Loading rate for the digestor was maintained at about 3.2 kg $VS/m^3/d$. Biological methane potential (BMP) assays (7) were conducted to determine the ultimate methane yields of the RDF used.

Steady State Samples

Collection of steady state samples commenced after the ETU had been operated for three hydraulic retention times. Feed and effluent samples were analyzed for TS, VS, pH, and VFA daily. Gas composition was analyzed daily. Alkalinity and NH_3-N were analyzed twice a week. Elemental analyses and heating value determinations were done on weekly composite samples of the feed and effluent.

Profile Samples

A sampler with an auger (2.86 cm od on a 1.27 cm shaft and a 2.54 cm pitch) in a 3.2 cm id pipe (Fig. 2) was used during test 3 to take profile samples. The sampler was inserted through side ports and an electric drill rotated the auger to withdraw samples that were collected from the side arm of the sampler. Eight samplers were installed on the ETU at a later date to allow taking profile samples to characterize the ETU.

A total of 10 sets of profile samples were taken over two 24-h periods. VFA, pH, TS, and VS were analyzed. The potential of microbial communities from various depths of the ETU to utilize acetate and other VFAs were assessed in a batch test similar to a BMP assay using one set of the profile samples. These samples were stored at 4°C overnight in plastic containers filled to a level of about 90% to reduce air contamination. The batch test was conducted using serum bottles with a nominal volume of 200 mL (actual 279.66 ± 0.8 mL with a butyl rubber stopper in place). Sixty milliliters of the samples were used along with 10 mL of test substrates in triplicate sets. One set received distilled and deionized water to serve as a control. The second set received 3.3 mmol of acetic acid (Fisher Scientific, Fair Lawn, NJ). The third set received a composite of acetic acid (0.41 mmol), propionic acid (0.69 mmol), and *n*-butyric acid (0.1 mmol). These

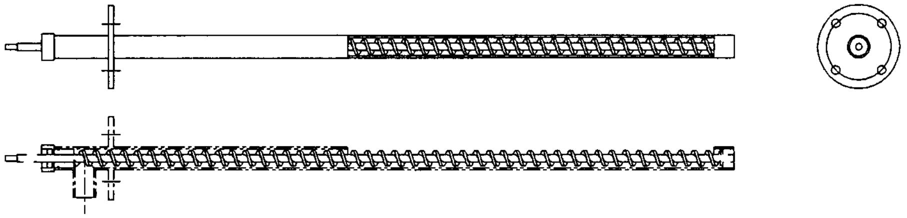

Fig. 2. Auger type sampler for taking profile samples from the ETU.

bottles were incubated in the dark at 35°C. Gas production was measured and gas composition analyzed periodically.

Analytical Procedures

TS, VS, and Alkalinity to pH 3.7 were analyzed according to the "Standard Methods" (*8*). The pH was measured with a pH meter. NH_3-N was measured with a selective ion probe (Orion 9512). VFA was analyzed with a Perkin-Elmer SIGMA 3B gas chromatograph equipped with a flame ionization detector. Gas composition was analyzed with a Fisher-Hamilton Gas Partitioner equipped with a thermal conductivity detector. Elemental analyses were done with Perkin-Elmer Elemental Analyzers by an outside lab. Heating value was obtained through bomb calorimetry.

RESULTS AND DISCUSSION

Operating conditions, along with physical and chemical characteristics of the feeds, are shown in Table 1. Fresh feed blends contained VFAs of about 1000 mg/L as acetate. The increase in VFAs in the feed indicates that fermentation and hydrolysis had occurred in the feed tank. The screw press was very effective in dewatering digestor effluent. However, some difficulties were encountered, and it was reequipped with a higher-power motor and is working well now.

ETU Performance

Steady state performance data of the ETU are summarized in Table 2. Although the alkalinity and NH_3-N concentrations in the effluent during test 3 were lower than those from the first two tests, performances of the ETU were comparable. Methane yields from all tests represented about 90% of the ultimate methane yields. Following test 3, a batch test similar to the BMP for the RDF was conducted to determine if chemical nutrients supplement would improve methane production rates. A composite sample was taken from ports 2, 5, and 8 of ETU to start the batch test. One set of three bottles received chemical nutrients in the same weight propor-

Table 1
Operating Conditions and Characteristics of the Feed[a]

	Test no.[b]		
	1	2	3
Operating conditions			
Temperature, °C	34.7	34.0	35.0
Feed introduction	Top	Top	Top
Effluent withdrawal, port no.	4–7 and bottom	5, 6, and bottom	Bottom
Hydraulic retention time, d	16	18	19
Daily recirculation time, h	4.2	4.1	0.3
Recirculation port nos.	1–4, 6	1–4	1–3
Feed characteristics			
Avg. TS in the feed, wt%	7.1	7.8	7.7
Avg. VS content in the feed, wt% TS	74.5	77.8	80.4
Avg TVA in the feed, mg/L acetic	7300	6300	6000
Avg. pH of the feed	6.0	5.9	5.0
Avg. alkalinity in the feed, mg/L $CaCO_3$	5800	5400	3200
Avg. NH_3-N in the feed, mg/L	1200	400	210
C/P ratio	100	100	NA
C/N ratio	15	20	51.3
C/S ratio	150	150	46.8
NH_4Cl added, mg/L	5640	2170	0.0
KH_2PO_4 added, mg/L	1100	590	0.0
Na_2S added, mg/L	260	140	0.0
$NaHCO_3$ added, mg/L	7600	4410	0.0
Ultimate BMP, m^3 CH_4/kg VS fed	0.30	0.30	0.26

[a] Samples taken during feeding operation. The age of the feed ranged from 1 to 6 d.
[b] Data for test no. 1 were collected from May 18 through June 21, 1987; data for test no. 2 were collected from Oct. 12 through Nov. 15, 1987; data for test no. 3 were collected from Aug. 1 through Aug. 29, 1988.

tions as those used in test 2, whereas the other set contained only the sample to serve as a control. The initial methane production rates were identical, and methane production remained identical for 30 d (Fig. 3). Chemicals were added to the ETU beginning October 1, 1988. Methane yields from the ETU before and after the addition of chemical nutrients were similar (Fig. 4) although NH_3-N and alkalinity concentrations were quite different. Thus, chemical nutrients addition probably had no effect on methane yields from the ETU.

Comparison of methane yields from the ETU and CSD reactor (Table 3) showed that the former was higher by 10–20%. The advantage of the ETU over CSD is obvious when the simplicity in design and the saving in mixing requirement are considered.

Table 2
Summary of Steady State Performance Data

	Test no.[a]		
	1	2	3
Performance data			
Avg. daily gas prod., m^3	5.8	5.6	5.0
Avg. methane content, vol%	58.6	58.6	58.2
Methane yield, m^3/kg VS fed	0.27	0.25	0.24
VS reduction, %	NA	NA	48
Effluent characteristics			
Avg. TS in effluent, wt%	6.2	6.1	4.5
Avg. VS in effluent, wt% TS	66.3	68.4	71.4
Avg. TVA in effluent, mg/L acetate	400	200	80
Avg. pH	7.2	7.1	6.8
Avg. alkalinity in effluent, mg/L $CaCO_3$	5900	5500	3540
Avg. NH_3-N in effluent, mg/L	800	300	240
C/H ratio	NA	NA	8.0
C/N ratio	NA	NA	38.8
C/S ratio	NA	NA	65.5
C/P ratio	NA	NA	545
Heating value, kJ/dry kg	NA	NA	16,674
Dewatered cake, %TS	NA	NA	42

[a]Data for test no. 1 were collected from May 18 through June 21, 1987; data for test no. 2 were collected from Oct. 12 through Nov. 15, 1987; data for test no. 3 were collected from Aug. 1 through Aug. 29, 1988.

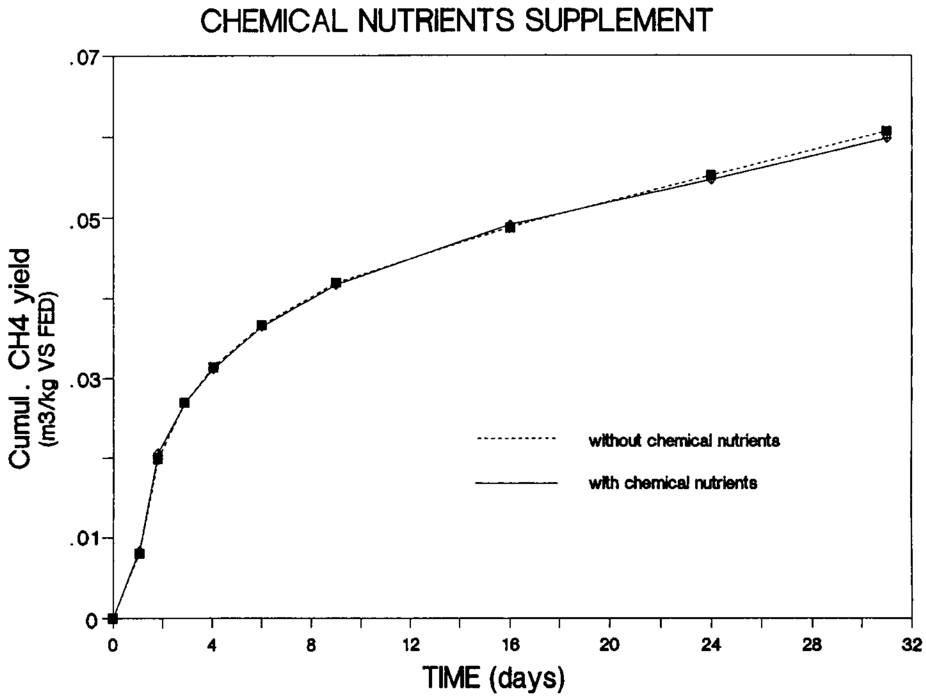

Fig. 3. Effect of chemical nutrients on initial methane production rate.

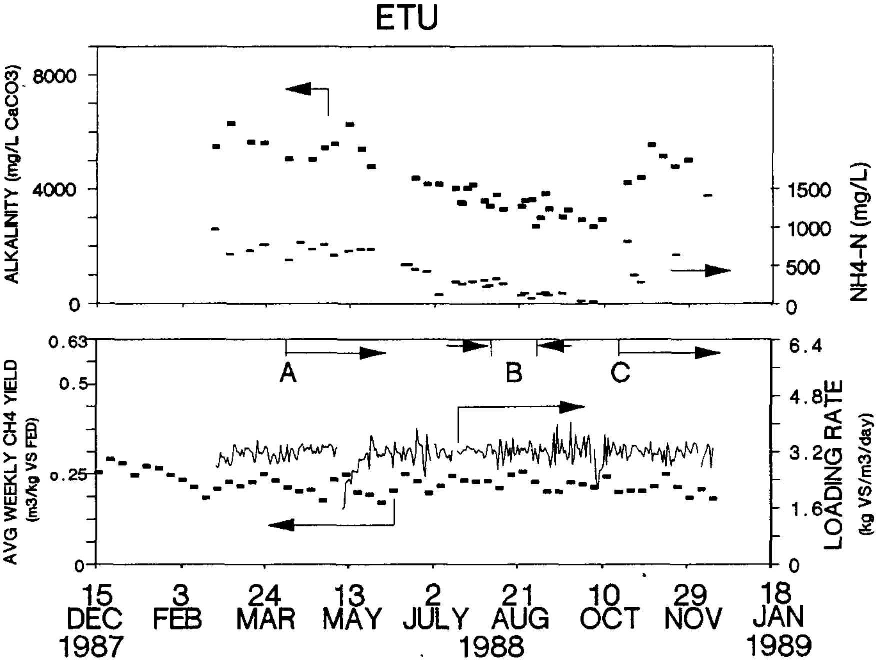

Fig. 4. Comparisons of ETU performance before and after chemical nutrients addition. (A), beginning of operation without chemical addition; (B), steady state period; and (C), beginning of operation with chemical addition.

Table 3
Comparison of Performance of ETU and CSD

Test no.[a]	Digestor type	Effluent characteristics %TS	VS, %TS	pH	VFAs, mg/L acetate	Alkalinity, mg/L $CaCO_3$	NH_3-N, mg/L	CH_4 yield, m^3/kg VS fed	$\%CH_4$
1	CSD[b]	5.5	66.3	7.2	670	5700	1230	0.21	59.2
1	ETU	6.2	66.3	7.2	400	5900	800	0.28	58.6
2	CSD	5.7	72.0	7.2	150	5400	310	0.20	59.7
2	ETU	6.1	68.4	7.1	200	5500	300	0.25	58.6
3	CSD	5.7	77.3	6.7	50	3520	120	0.21	58.4
3	ETU	4.5	71.4	6.8	80	3530	240	0.24	58.2

[a] Data for test no. 1 were collected from May 18 through June 21, 1987; data for test no. 2 were collected from Oct. 12 through Nov. 15, 1987; data for test no. 3 were collected from Aug. 1 through Aug. 29, 1988.
[b] CSD stands for continuously-stirred digestor, fed once a day.

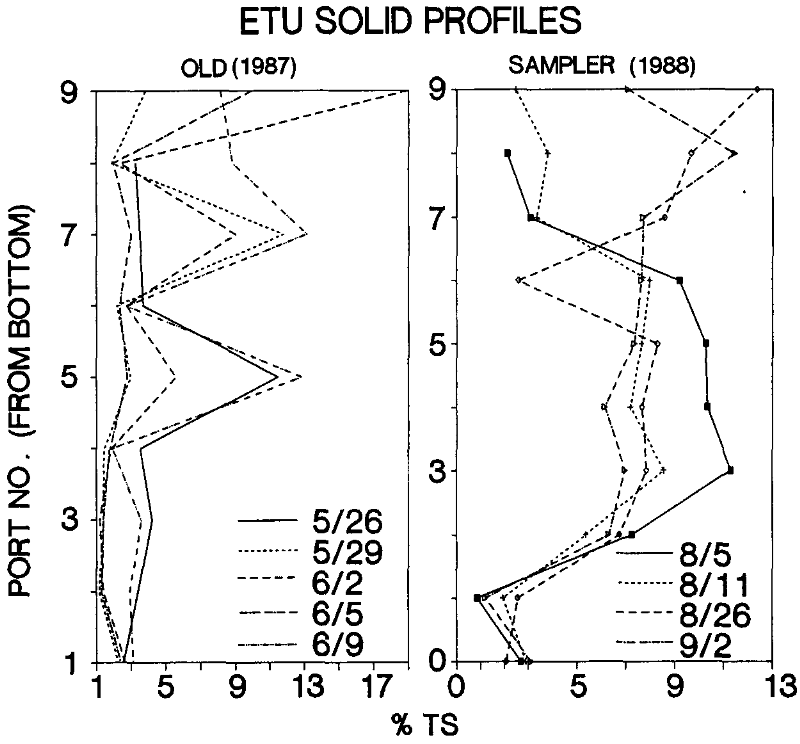

Fig. 5. Comparison of total solids distribution profiles obtained with and without a sampler. (OLD, 1987), without a sampler; (SAMPLER, 1988), with a sampler.

Sampler Performance

Since the ETU is a nonmixed downflow digestor, its solids distribution pattern should be reasonably stable. One way to determine if the sampler was producing better profile samples is to compare the consistency of samples generated with and without the sampler. A comparison of TS profiles sampled during steady state periods of test 1 (without a sampler) and 3 (with a sampler) is presented in Fig. 5. TS profiles up to port 6, as obtained with the sampler, were more consistent than those without. Samples taken from the upper three ports were inconsistent. An explanation for this could be a lack of a hydraulic head at the upper region of the ETU since the sampler relied on pressure to force feed samples into its opening. This was particularly important owing to the fibrous nature of the samples, the tendency of the RDF to float and trap gas bubbles, and the relatively small diameter of the sampler.

ETU Characteristics

The solids, pH, and VFA profiles of the ETU over a 24-h period are shown in Fig. 6. Solids concentrated on the upper region of the digestor;

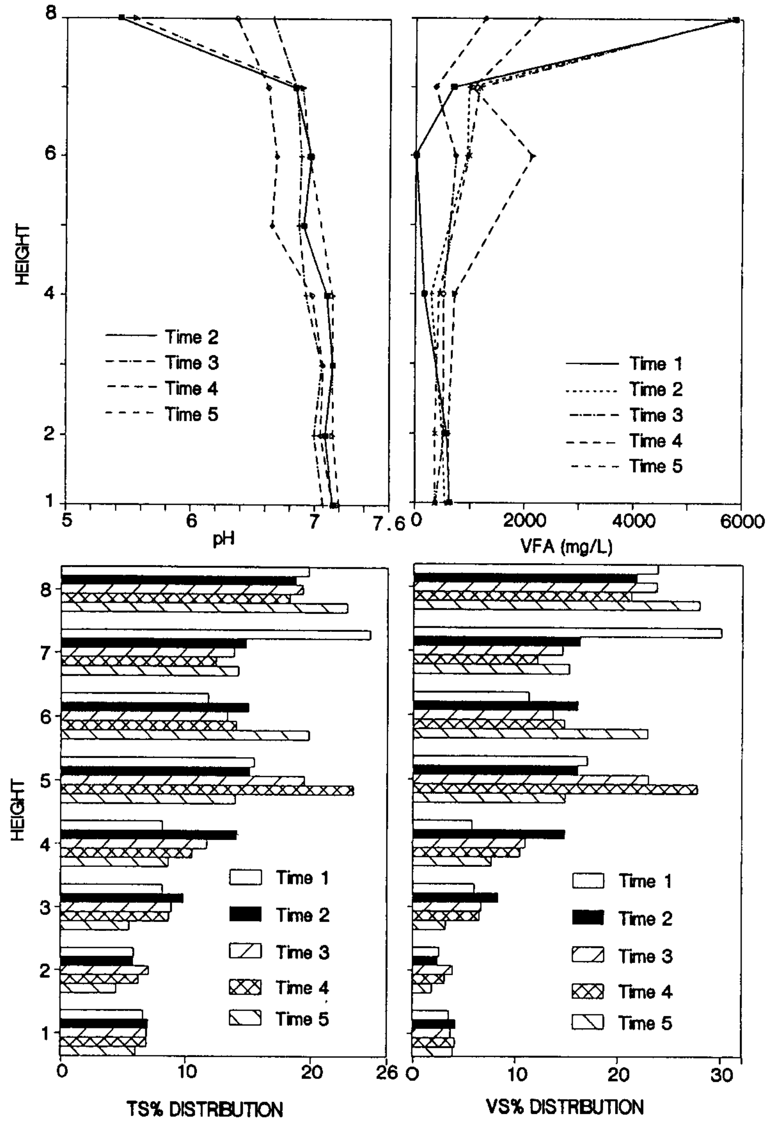

Fig. 6. ETU TS, VS distribution, pH, and VFA profiles over a 24-h period. Bars represent the percent of total TS or VS in the ETU at various depths. Time 1, at regular effluent withdrawal time; Time 2, 4 h after feeding and about one-tenth of the volume turnover; Time 3, 3 h since Time 2 and about 2 h after one-tenth of volume turnover; Time 4, 3 h after Time 3; and Time 5, regular effluent withdrawal time, the next day.

thus, a longer solid retention time than the hydraulic retention time was possible. The solid retention time during test 3 was 26 d. This was probably the reason for higher methane yields in the ETU than in the CSD. Samples from port 8 had significantly higher VFA and lower pH than the others, indicating active acidogenesis. Phase separation was obvious. Methanogenic activity tests indicated the highest potentials for volumetric methane

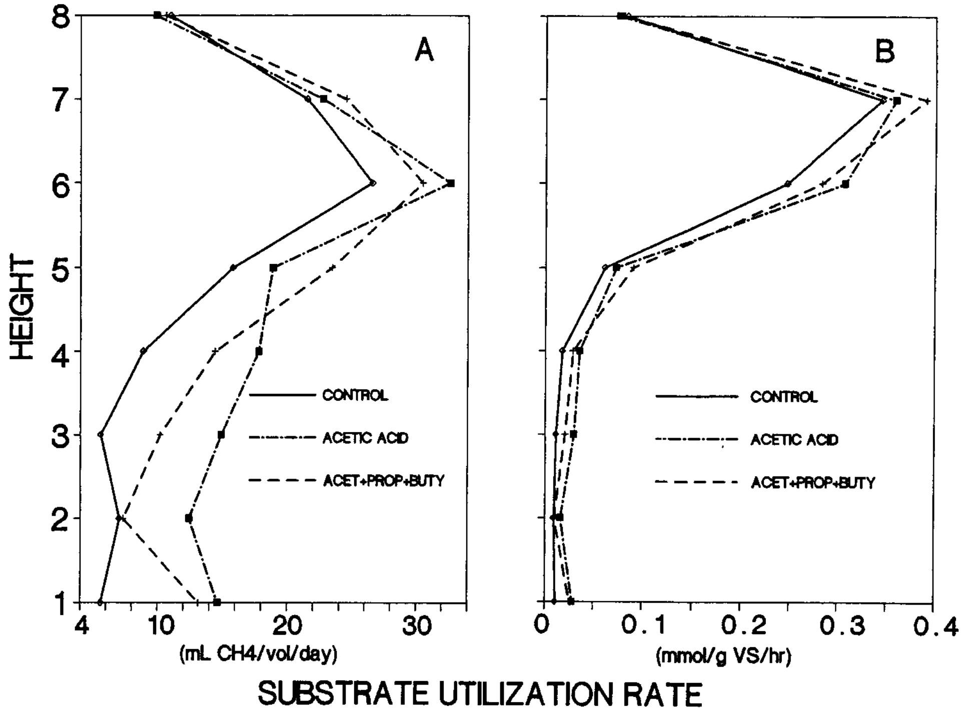

Fig. 7. Potential methanogenic activities of microbial communities at various depths of the ETU. ETU was fed from the top and effluent withdrawn from the bottom. Assay was performed with 60 mL of samples in serum bottles. A), volumetric production rate expressed as per volume of sample; B), specific production rate expressed as per gram of VS.

production rate at port 6 (Fig. 7, A) and specific methane production rate at port 7 (Fig. 7, B). These observations show that the solid concentrating digestor offers an alternative for extending solid residence time without requiring a large digestor volume.

CONCLUSIONS

The following conclusions were drawn from this study

1. The ETU outperformed the CSD digestor in methane yield by about 10–20%.
2. The ETU treating RDF/sludge, and operated in a downflow mode, passively concentrated solids on the upper region of the digestor. Microbial activities were most active in this region.
3. It was technically feasible to recycle effluent supernatant. However, it may be necessary to supplement the feed with some nitrogen for stability reasons.

4. We now have a better mechanism to obtain samples from the ETU. The samplers provide a way to study solids distribution, microbial activities at different depths, and effects of recirculation on solids distribution.

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