Anaerobic Treatment of Raw Domestic Sewage at Ambient Temperatures Using a Granular Bed UASB Reactor

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Summary

Results obtained in a 120 liter 2 m high UASB-reactor with raw domestic sewage and using a granular sugar beet waste cultivated seed sludge, reveal the feasibility of this type of anaerobic treatment for domestic sewage. Under dry weather conditions 65–85% COD reduction can be achieved at temperatures in the range of 8–20°C and at hydraulic loads as high as 2 $m^3 \cdot m^{-3} \cdot day^{-1}$. In the case of heavy rainfall the COD-reduction drops to 50–70% and occasionally, viz. at very low influent COD, even below 50%. The net methane production amounts to 7.1–7.3 $m^3 \cdot PE^{-1} \cdot year^{-1}$, and the excess sludge production ranges from 5.0–8.6 kg TS $\cdot PE^{-1} \cdot year^{-1}$. Regarding the results obtained anaerobic treatment of raw sewage not only looks an attractive proposition for tropic areas but also for moderate climatic areas.

INTRODUCTION

Despite the potential energy savings in applying an anaerobic treatment, most of the conventional wastewater treatment processes developed and applied so far are based on energy-intensive aerobic technology. Anaerobic processes are traditionally considered inadequate for low strength wastes and temperatures below 20°C. However, in view of results of recent research work with newly developed processes such as the anaerobic filter (AF), the upflow anaerobic sludge blanket (UASB) process, and the more recently developed attached film expanded bed (AAFEB) process, and in view of the improved insight obtained into the effects of environmental factors on the process, the gradually improving comprehension of the biochemistry and microbiology of the process, the application of anaerobic digestion for the treatment of low strength wastes—even at lower temperatures—may be well foreseen. Anaerobic treatment may become particularly attractive as an alternative for treating the wastewater of isolated communities, restaurants, hotels, camp sites, etc., because in many of these cases there is a need for compact, simple, and inexpensive devices for waste treatment. In fact, the development of improved septic tank systems capable of giving a considerably higher treatment efficiency

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at the same degree of simplicity in design as conventional septic tank systems would be very welcome. Evidently, this holds particularly for areas where the disposal of effluent from conventional septic tank systems becomes difficult, for example, due to tight soil conditions, a high water table, or a limited availability of open land. Moreover, in many Third World countries there is a need for simple and inexpensive sewage treatment systems by which a high treatment efficiency can be achieved.

Coulter, Soneda, and Ettinger[1] were the first to demonstrate the feasibility of anaerobic digestion for the treatment of domestic wastewater. They applied a two-stage process consisting of a 4.7-m^3 cone-shaped sludge contact tank as the first step followed by a 2.6-m^3 rock-packed AF of ca. 1.2 m height (total liquid capacity of the filter was 1.5 m^3). The results obtained (see Table I) were quite encouraging both from the point of view of BOD as well as TSS reduction, since the process was started unseeded and relatively high BOD and TSS reductions were already achieved four to six weeks after the startup of the process. The main part of the BOD and TSS reduction was obtained in the first stage of the process. Moreover, from the 72.6 kg TSS removed, only 11.4 kg accumulated in the system. Based on these pilot plant experiments Fall and Kraus[2] investigated the process in a 12 × 6 × 5.2-m demonstration anaerobic contact tank for 350 houses.

The raw sewage was introduced into the tank via eight downcomers spaced along both longitudinal walls and the effluent was collected in a central longitudinal through. The system was started unseeded in conformance to the experiments of Coulter. As it appears from the results shown in Table I the performance with respect to BOD treatment efficiency was quite disappointing; this was particularly the case during the summer time, viz., only 10–20% BOD reduction against 30–50% BOD reduction during winter time. The poor performance of the demonstration plant presumably should be mainly attributed to the fact that the plant was started up during winter time, whereas Coulter started his experiments during the summer. Due to the low-temperature conditions applied in the startup of the demonstration plant (i.e. 10°C), anaerobic organisms were unable to develop in sufficient amounts, and at the time that the temperature of the wastewater was raised, hydrolysis of the large amount of accumulated solid substrate initiated a severe overloading of the methanogenic flora present. Much more encouraging are the results obtained in South Africa by Simpson[3] using a 1.7-m^3 contact process combined with two 0.45-m^3 settlers placed in series, and by Pretorius[4] in laboratory experiments and in pilot plant (2 m^3) experiments with a two-step process similar to that of Coulter. In both cases, the treatment temperature exceeded 20°C. This was also the case in the experiments conducted by Raman and Khan[5] with raw and settled sewage in laboratory scale AF systems (10.8 cm diameter, packed with 2–2.5 cm stones to a height of 120 cm) and in pilot plant scale AF (1.61 × 1.61 × 1.40-m boxes packed with 2.5–3.5 cm stones to a depth of 120 cm). The results obtained by Raman and Khan clearly illustrate that the pro-

TABLE I
Summary of Literature Data Concerning Anaerobic Treatment of Domestic Sewage

Raw Waste				Conditions		Treatment efficiency percent					
BOD	COD (mg/L)	TSS	TOC	Temperature (°C)	HRT (h)	BOD	COD (% reduction)	TSS	TOC	Experimental arrangement[a]	Reference
210-320	—	260-360	—	summer	24	48-65	—	90-95	—	AF+CT pilot	1
242	528	368	—	10-16	22.4-13.4	35-50	—	72-80	—	CT demonstration	2
242	528	368	—	16-21	22.4-13.4	35-50		77	—		
372-386	1207-1284	—	—	26.7	15	91(96)[c]	78(92)[c]	—	—	CT+BT pilot	3
372-386	1207-1284	—	—	19.6	22	86(95)	72(90)	—	—		
372-386	1207-1284	—	—	22.8	13.5	84(94)	70(90)	—	—		
372-386	1207-1284	—	—	22.0	12	78(93)	69(80)	—	—		
	ca. 500	—	—	20	24	72-90	60-65	—	—	CT+AF pilot	4
60-180	—	60-210	30-120	11-25	—	ca. 50	—	65-80	60-80	AF pilot	6
60-210	—	34-187	—	25-32	5	80	—	71	—	AF lab	
113-282	250-572	68-203	—	25-33	5	83.8	71	85.8	—	AF lab	5
115-238	—	109-172	—	27.5	6.4[b]	72.5	—	56.8	—	AF pilot	
112-310	—	59-336	—	31	6.4[b]	79.5	—	88.5	—	AF pilot	
—	119-205	—	—	20	8-24	—	68-72	—	—	AAFEB lab	12
—	215	—	—	20	2	—	77	—	—	AAFEB lab	
—	140-220	—	—	20	2-1	—	57-84	—	—	AAFEB lab	
—	170-320	—	—	20	8	—	68-92	—	—	AAFEB lab	

[a]AF—anaerobic filter; CT—contact tank, BT—biolytic tank, AAFEB—anaerobic attached film expanded bed.
[b]During 9 h/day
[c]Values between brackets are based on filtered samples.

cess potentially is quite attractive for tropical areas. According to recent results obtained by Genung et al.[6] in a 5.67-m^3 pilot plant AF (150 cm diameter and 560 cm height, packed with ceramic Raschig rings), anaerobic treatment of sewage should not be excluded even at temperatures as low as 11–13°C.

Similar conclusions can be drawn from the results shown in Table II, which were obtained in 30–120-L UASB experiments with raw domestic sewage in our laboratory.[7,8] These experiments were conducted using digested sewage of a rather poor specific activity as seed in the UASB reactors.

Obviously, even significantly better results may be expected if a high-grade quality seed material could be used, for example, such as the granular type of sludge produced in the treatment of sugar beet waste and potato processing waste water. As was reported elsewhere,[7-10] this granular sludge is high in specific activity (ca. 1.0 g COD g VSS^{-1} day^{-1} against less than 0.1 g COD g VSS^{-1} day^{-1} for digested sewage sludge) and exerts superior settling characteristics.

At present, at least six full-scale UASB plants have been put in operation in the Netherlands on both types of wastes, and consequently it may be projected that sufficient quantities of granular seed sludge will be available as seed material in the course of a few years. Since there is increasing interest in applying the UASB process in other countries, such a situation may arise in due time elsewhere. In view of these considerations, we decided to investigate the use of granular sugar beet waste adapted sludge in an UASB pilot plant for treating raw domestic sewage. The experiments were started in May 1979. At the same time, 6-m^3 UASB pilot experiments were also started using digested sewage sludge as inoculum. These experiments, conducted at a treatment temperature of 13-20°C, also gave quite promising results, viz. 65–85% COD reduction at 20°C, and 55–70% COD-reduction at 13–17°C under dry weather conditions and 17–14-h liquid detention times.[11]

An interesting future approach may be the "attached film expanded bed" process (AAFEB), which recently was introduced by Jewell, Switzenbaum, and Morris.[12] However, so far the AAFEB process has only been applied at the small bench scale and with primary settled sewage.

EXPERIMENTAL

Apparatus

The UASB pilot plant used in the experiments consisted of a 28.8-cm-diameter plexiglass cylinder (170-cm height) with a conical-shaped bottom (20.5-cm height). In the upper part, the reactor is equipped with a combined gas collector/settler device. The total reactor volume is 120 L, i.e., 108 L for the digester compartment and about 15 L for the settler. As shown in the schematic diagram in Figure 1, sample ports are arranged over the height of the reactor, the first 5 cm above the inlet of the feed, the others at 20–40-cm inter-

TABLE II
Experimental Results Obtained with Raw Domestic Waste Using 30–120-L UASB-Reactors

Experiment number	UASB reactor Volume (L)	UASB reactor Height (m)	Hydraulic load ($m^3\ m^{-3}\ day^{-1}$)	Surface load (m/h)	Temp. range (°C)	Duration of exp. period (days)	COD_{tot} (mg/L)	Dissolved fraction of COD (%)	COD reduction Total[a] (%)	COD reduction Dissolved[b] (%)	SS reduction (%)
II	30	1	3.8	0.16	30	6	480–660	67–76	62–75	51–57	—
II	30	1	2.7–2.8	0.11–0.16	23	21	330–520	48–67	54–68	20–52	30–75
IIIA	30	1	1.2	0.05	21	26	700–860	56–68	50–78	50–55	70–80[c]
IIIB	30	1	1.2	0.05	21	26	700–860	56–68	52–77	50–55	—[c]
IIIA	30	1	2.6	0.11	26	71	550–760	66–73	58–72	54–57	50–80[c]
IIIB	30	1	2.6	0.11	26	63	550–760	66–73	54–73	55–60	50–80[c]
IIIB	30	1	3.6	0.15	26	6	530–570	75–80	55–69	ca. 50	50–70
IIIB	30	1	3.6	0.15	21	12	420–620	77–85	59–70	55–60	20–60
IIIB	30	1	2.6	0.11	21	24	520–590	73–75	57–79	50–60	30–70
IV	120	1.75	1.2	0.08	16–18	40	450–910	47–71	55–75	20–60	55–80
IV	120	1.75	2.0	0.145	18–21	65	700–1200	40–60	72–78	25–60	70
V	120	1.75	1.6	0.12	13–17	28	450–730	62–85	50–68	21–51	90[d]
V	120	1.75	1.0	0.07	14–17	17	470–750	69–85	49–63	27–55	90[d]
V	120	1.75	0.6–0.75	0.04–0.05	12–18	110	420–920	55–95	48–70	30–45	90[d]

[a]Based on raw influent and filtered effluent samples.
[b]Based on filtered influent and effluent samples.
[c]Parallel experiments in two identical UASB reactors.
[d]In these experiments, the effluent weir contained a sponge in order to reduce washout of sludge.

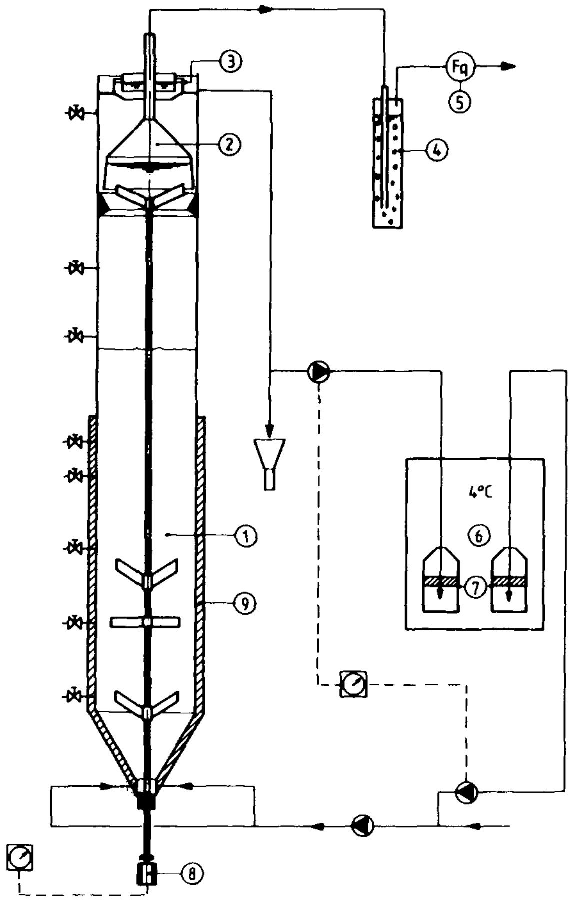

Fig. 1. The experimental arrangement used in the experiments with raw sewage: (1) digestion compartment, (2) gas collector, (3) effluent weir, (4) water gauge, (5) wet test gasmeter, (6) refrigerator, (7) containers for effluent and influent samples, and (8) timer controlled stirrer.

vals. The width between the gas collector and the reactor wall was 10 mm, leaving a free area here of 0.87 dm^2.

Although the reactor was equipped with a stirring assembly, stirring was rarely applied during the whole experimental period.

The lower 96 cm of the reactor was insulated with a 1-in.-thick rubber jacket in order to prevent warming up of the reactor contents in this part of the reactor.

Seed Sludge

The experiment was started using 75 L of sugar beet cultivated (5.65% DS, 77.5% VS) sludge.

The maximum specific activity of the seed sludge, as measured in a batch experiment with a VFA mixture of 600 mg/L C_2, 600 mg/L C_3, and 600 mg/L C_4, amounted 0.8–1.0 kg COD kg VSS^{-1} day^{-1} at 30°C.

Wastewater Characteristics

The experiments were carried out with raw domestic sewage of the village Bennekom, which has a combined sewer system. The COD_{tot} and SS content (COD_{SS}) wastewater varied from 140–1100 mg COD_{tot}/L and 6–800 mg COD_{SS}/L. These wide fluctuations can also be attributed to the fact that holding tanks have been installed at the municipal sewage treatment plant.

Temperature

The experiments were conducted at the ambient temperature of the sewage. However, due to the fact that the installation was placed in an experimental hall of ca. 15°C, and only the lower part of the reactor was insulated, during winter time the effluent left the reactor at temperatures being 3–5°C higher than of the raw waste.

Sampling and Analyses

Sampling of influent and effluent was made using timer-controlled peristaltic pumps, which pumped 100–200 mL/h of the influent and effluent solutions into containers, which are placed in a 4°C refrigerator. The containers were equipped with a piston in order to prevent uptake of oxygen in the solution.

Analyses were made in 24- or 48-h composite samples, except during the first months when the effluent analyses were made on graft samples. COD, BOD, and TS analyses were made according to standard methods. Gas analyses for CH_4, CO_2, and N_2 were made using a column with Porapack-8 for detection of CO_2, and a molecular sieve 5A for the separation of the other gases, (column temperature, 60°C; carrier gas, He; injection temperature, 75°C).

The VFA were also determined by gas chromatography (1-m glass column with 60–80 chromosorb, 30% Tween 80, and N_2 carrier gas saturated with formic acid; the column temperature was 120°C and injection temperature and detector temperature were both 170°C, FID).

RESULTS

The results presented in this article cover a period of 17 months of almost continuous operation, from May 1979 to October 1980. Raw and filtered influent and effluent COD values and the COD reduction calculated from the raw influent and filtered effluent COD are shown in Figure 2 and Table III together with the influent and effluent temperatures and the detention time applied.

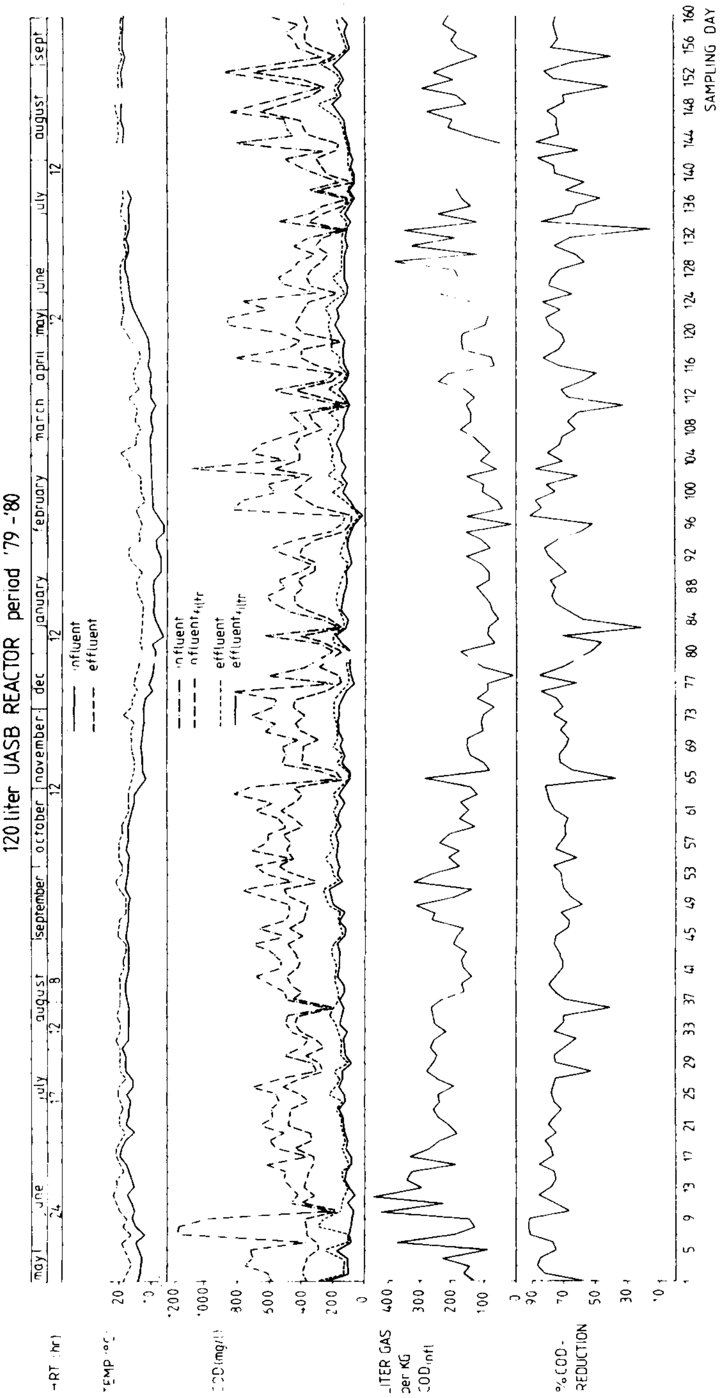

Fig. 2. Experimental results obtained over the whole experimental period in the 120-L UASB reactor.

TABLE III
Experimental Data Obtained over Various Periods of the Experiment in the 120-L UASB Reactor

		Influent COD				Effluent COD				Treatment efficiency			
		Raw		Filtered		Raw		Filtered					
Period	Number of samples	Range (mg/L)	Average (mg/L)	Range (mg/L)	Average (mg/L)	Range (mg/L)	Average (mg/L)	Range (mg/L)	Average (mg/L)	E_{tot} (%)	E_{diss} (%)	Gas production L/kg COD_{infl}	temp. (°C)
(1979)													
17/5-31/5	6	588-754	666	361-386	374	127-304	177	95-253	127	81	66	110	13-15
11/6-15/6	9	363-1253	948	262-371	309	79-294	154	40-181	102	89	67	108	14-15
18/6-29/6	10	204-608	467	182-439	341	99-157	129	60-128	97	79.5	71.5	320	12-16
4/7-30/7	12	307-703	504	227-513	366	100-227	157	81-163	131	74	64.5	171	16-19
7/8-29/8	13	222-709	523	202-486	415	139-215	181	107-172	143	73	65.5	204	17-18
4/9-27/9	9	451-761	585	302-537	429	150-265	196	115-227	168	71.5	61	195	17.5-16.5
2/10-31/10	10	459-824	625	387-522	459	153-250	194	125-186	161	74	65	182	17.5-13
1/11-29/11	11	156-720	491	145-454	349	98-202	166	97-182	147	70	58	124	13-11.5
(1980)													
3/12-18/12	5	200-820	513	144-436	257	100-189	132	75-144	108	79	58	113	12-9
2/1-30/1	15	153-629	434	147-452	337	100-203	153	93-190	125	71	63	94	9.5-6.5
1/2-29/2	11	144-1100	546	86-572	322	35-235	154	10-157	112	79.5	65	85	6.5-10
4/3-31/3	9	146-662	426	97-450	318	119-245	190	110-184	148	65	54	132	8.5-10.5
2/4-9/5	8	195-866	581	135-450	330	113-231	190	101-187	141	76	57	123	10-14
4/6-30/6	10	295-768	472	156-388	291	121-253	175	105-184	130	72.5	56	176	15-18
2/7-31/7	12	117-539	322	69-359	235	72-155	109	63-126	90	68	62	150	16-17
1/8-30/8	12	254-882	542	162-666	383	101-299	176	100-203	148	72.5	61	187	16-18
1/9-8/9	6	248-581	433	163-376	323	104-175	146	93-150	122	72	62	192	18-19.5

COD Reduction

In order to obtain a clearer picture of the effect of the treatment temperature and of the fraction of suspended solids contained in the waste, the results obtained over the whole period have been arranged in Figures 3 and 4 for three raw influent temperature ranges, viz. 15–20°C (summer time), 10–15°C (fall and spring), and 5–10°C (winter time). Moreover, the date were also differentiated according to the suspended fraction of COD in the waste, i.e.

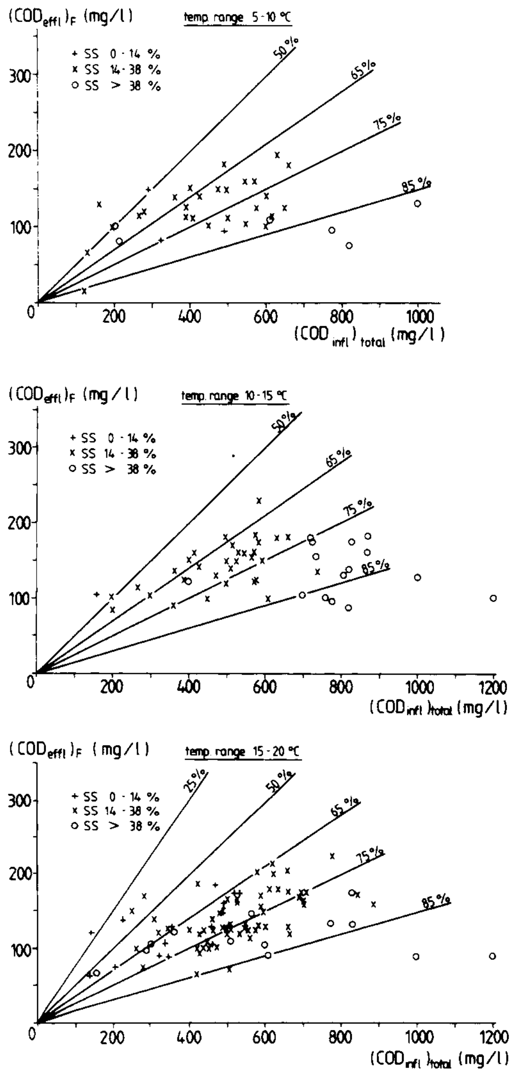

Fig. 3. Filtered effluent COD in relation to the raw influent COD for three temperature ranges.

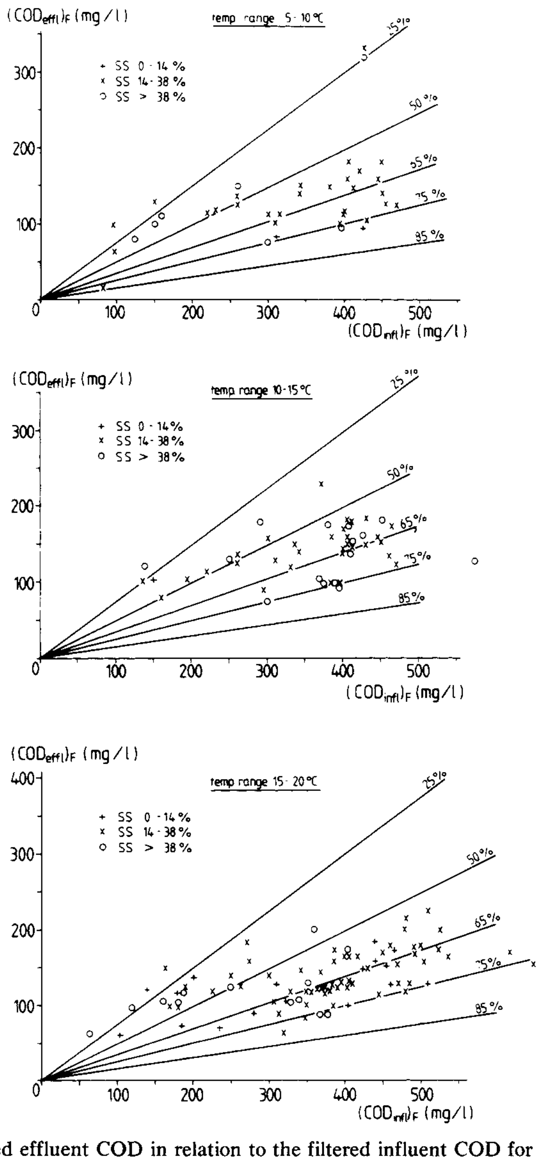

Fig. 4. Filtered effluent COD in relation to the filtered influent COD for three temperature ranges.

0–14%, 14–38%, and greater than 38%. Figure 3 shows the filtered effluent COD in relation to the raw influent COD, and Figure 4 gives the filtered effluent COD in relation to the filtered influent COD.

The highest overall treatment efficiencies were obtained with sewage having a high fractional content of suspended matter and for influent COD values exceeding 400–500 mg/L. The overall COD reduction is between 65 and 90% in that case. With highly diluted sewage (< 300 mg/L), the overall COD reduction is between 50 and 65%, and occasionally below 50%. The results in Figure 3 clearly illustrate that the treatment efficiency is only slightly affected by the temperature.

The efficiency of the process with respect to the removal of dissolved organic matter is distinctly lower than the overall COD reduction, but still the majority of the data obtained is in the range of 50–75% COD reduction, even in the temperature range 5–10°C. Obviously, the rate of formation of dissolved organic matter (i.e. the rate of hydrolysis) was always smaller than the removal rate.

Treatment Efficiency on TOC and BOD Bases

Results of TOD and COD measurements made during a number of days are summarized in Table IV, together with the corresponding treatment efficiencies. In most cases, the treatment efficiency based on TOC is slightly higher than that based on COD. Results of influent and effluent BOD and COD measurements revealed that the COD/BOD ratio is in the range 1.7–1.9 for the raw sewage and 2.4–2.9 for the effluent of the anaerobic reactor.

Gas Production

The gas production, expressed as L gas/kg $COD_{supplied}$ is clearly affected by the treatment temperature (cf. Fig. 2). During summer time, the average gas production is 220 L/kg $COD_{supplied}$, but during fall and spring the gas production decreases to approximately 135 L/kg $COD_{supplied}$ and during winter time to approximately 100 L/kg $COD_{supplied}$. Fluctuations in the influent COD are reflected in the gas production, although with a delay of a few days. Moreover, the fluctuations are less pronounced than for the influent COD values. Over the first year, in which the process has been in operation for 350 days, 6.99 m^3 of biogas was produced from 72 m^3 of raw domestic sewage.

Gas Composition

Gas chromatographic analyses indicated that the gas contained only 2–4% CO_2, but the fraction of nitrogen was relatively high, i.e., between 14 and 22% dependent on the amount of gas produced. The higher the gas production per unit of volume of sewage treated, the lower is the N_2 content and the higher the CH_4 content. The nitrogen in the biogas originates from the dissolved nitrogen in the influent solution; it is stripped from the liquid phase by the methane gas produced in the fermentation process.

Solids Accumulation and Characteristics

During the whole experimental period considered, only 1 L of sludge (with 5% TS) was discharged from the reactor. Results of TS measurements made over the height of the column (Table V), indicate that after one year of almost

TABLE IV

TOC and COD Treatment Efficiencies as Measured for a Number of Days

Day number	Influent characteristics (mg/L)				Effluent characteristics (mg/L)				Treatment efficiency (%)					
	COD		TOC		COD		TOC		COD			TOC		
	Total	Filtered	Total	Filtered	Total	Filtered	Total	Filtered	E_r/I_r[a]	E_f/I_f[b]	E_f/I_r[c]	E_r/I_r[a]	E_f/I_f[b]	E_f/I_r[c]
94	593	394	165	116	149	106	90	32	74.9	73.1	82.1	69.7	72.4	80.6
95	444	317	134	92	121	114	26	26	72.7	64	74.3	80.6	71.7	80.6
97	144	96	85	—	79	72	36	—	45.1	25	50	57.6	—	—
99	829	286	182	86	178	131	42	36	78.5	54.2	84.2	76.9	58.1	80.2
100	778	372	288	114	124	96	32	24	84.1	74.2	88.3	88.9	78.9	91.3
—	—	—	384	170	—	—	44	28	—	—	—	88.5	83.5	88.5
101	611	394	222	137	132	117	48	38	78.4	70.3	80.9	78.4	72.3	82.9

[a] E_r/I_r is based on unfiltered influent and effluent samples.
[b] E_f/I_f is based on filtered influent and effluent samples.
[c] E_f/I_r is based on filtered effluent and unfiltered influent samples.

TABLE V
SS Concentration Measurements Made on days 5, 31, 85, and 133 over the Height of the Reactor

	Day 31	Day 85			Day 133		
Height from bottom (cm)	SS (g/L)	SS (g/L)	VS (%)	COD (g/L)	SS (g/L)	VS (%)	COD (g/L)
5	63.6	65.1	85	—	54.3	81	51.1
25	62.5	72.3	87.3	—	57.8	82	60.3
45	64.3	64.1	88.7	—	56.3	81	49.5
63	63.7	59.4	88.2	—	44.1	78	54.9
73	54.5	57.3	86.7	—	39.2	76	45.1
111	35.4	47.5	87.1	—	38.1	73	49.7
130	25.8	0	—	—	38.3	73	54.7
170	—	0	—	—	0	—	—

continous operation (except during a 11-day break during Christmas 1979 and due to incidental clogging of influent, which, expressed in days, may have been 7 days at the maximum) the reactor still was not completely full with sludge.

Accurate measurements of the total amount of TS in the reactor are difficult to make, because occasionally smaller or larger parts of the sludge blanket are lifted. Moreover, representative sampling through the sampling taps is difficult because the TS content of the sludge bed is relatively high and sludge particles and flocs are rather large in size, especially in the lower part of the column containing the main part of the granular (seed) sludge. A more or less flocculant sludge occurs in the upper part of the reactor. This flocculant sludge also has excellent settling characteristics, as can be deduced from the TS content of the samples taken from the upper part of the reactor.

Washout of Sludge

The wash-out of sludge from the reactor can easily be derived from the filtered and unfiltered effluent COD values shown in Figure 2. Averaged over the first 11 days approximately 60 mg sludge COD/L_{effl} was removed from the reactor; during the period 11-77, the average SS_{COD} in the effluent was only 28.5 mg/L, and in the period 77-124, it amounted to 43 mg/L.

The main part of the SS in the effluent solution always consisted of easily settling flocs and particles and, consequently, in practice, the SS COD content in the effluent presumably can be maintained below approximately 10 mg/L with simple means. For this reason, the presented treatment efficiencies as calculated on the basis of filtered effluent and unfiltered influent COD values give a realistic picture of the treatment potentials of anaerobic treatment of domestic average.

Gas Production in the Absence of Feeding

During the 11 days feed interruption in the December-to-January period a total of 72 L gas was produced at a temperature of 12–15°C which gives an average gas production of 6.5 L/day over this period. The 72 L of gas corresponds to approximately 200 g CH_4 COD. The main part of the methane produced undoubtedly results from the accumulated excess sludge at that time, which is approximately 2.84 kg sludge COD. Consequently, approximately 7% of the excess sludge was converted to CH_4 COD during this 11-day break in the feeding.

DISCUSSION

COD Balances

In evaluating the results in terms of COD balances, the solubility of methane, nitrogen, and carbon dioxide in aqueous solutions should be taken into account, because in view of the high COD value of methane on a weight basis and the relatively low COD values of domestic sewage, the amount of methane in terms of the COD leaving the system via the aqueous phase is rather high. Moreover, since the solubility of CH_4 on a volume basis is about twice as high (see Table VI) as N_2, the volume of N_2 in the biogas undoubtedly is smaller than the volume of (dissolved) methane gas leaving the system with the effluent solution, more because the effluent solutions presumably is over saturated with CH_4.

As a consequence, the total volume of CH_4 produced in the process presumably exceeds the measured volume of biogas, in which the CO_2 content was always below 5%. Therefore, the methane production over the first 350 days of the experiment is at least equal to the total amount of biogas produced, which was 6.99 m^3. Another difficulty in making the COD balance is estimating the total amount of the COD supplied to the reactor, because sampling and/or COD analyses were not made for all days of the experiment but more or less randomly during working days. However, since the COD measurements were made on composite samples and 70–80% of the experimental days

TABLE VI
Solubility of Some Relevant Gasses in Water (mL of Gas Reduced to 0°C and 760 mm Hg, per Liter of Water when the Partial Pressure is 760 mm Hg)

Gas	0°C	10°C	20°C	30°C
CH_4	55.6	41.8	33.1	27.6
N_2	23	18.5	15.5	13.6
O_2	49.3	38.4	33.4	26.7
CO_2	1710	1190	878	665

were sampled, the histogram of COD_{infl}-values presumably approaches closely the actual situation, and consequently the deviations of the calculated average COD_{infl} = 525 mg/L will not exceed 25 mg/L. The same applies for the average COD reduction, which is 75% and certainly will not deviate more than 3% from what it actually has been. Based on these figures and a sludge washout of 40 mg COD/L, a rather realistic estimate can be made for the maximum and minimum value of the amount of accumulated sludge ($\Delta sludge_{acc}$). The figures presented in Table VII indicate that $\Delta sludge_{acc}$ is in the range 3.3-7.7 kg COD (2.5-5.8 kg TS), which corresponds to a volume of 50-116 L. Since only 60-65 L of the reactor was available for excess sludge at the start of the experiment and the reactor was almost full with sludge at day 350, the figures obtained indeed seem representative for the actual situation. The actual amount of accumulated sludge is close to the estimated minimum of 3.3 kg COD, which virtually looks quite reasonable in view of the fact that the CH_4-$COD_{produced}$ presumably was closer to 21 kg than to 19.1 kg.

Concerning the *excess sludge production* ($\Delta sludge_{AT}$), i.e. the sum of the sludge accumulated in the reactor and washed out from the reactor, the data in Table VII reveal that the estimated amount of sludge from the 72 m^3 of raw sewage treated is in the range of 6.1-10.6 kg COD, which corresponds to 6.45-11.2 kg sludge COD $(PE)^{-1}$ $year^{-1}$ or 5.0-8.5 (kg DS) $(PE)^{-1}$ $year^{-1}$. The total number of PE treated was estimated at 345 by taking for 1 PE 0.135 kg COD and 175 L of waste. Compared to the excess sludge production of a conventional aerobic treatment system combined with sludge digestion, for which the estimated excess sludge production is 20 kg DS $(PE)^{-1}$ $year^{-1}$,[13] in the anaerobic pretreatment only 25-40% of the amount of excess sludge is produced. To this amount approximately 3 kg TS $(PE)^{-1}$ $year^{-1}$ has to be added as excess sludge from the aerobic post treatment (i.e., at a 98% BOD reduction and a sludge yield of 0.8 kg TS/kg BOD). The picture for applying a combined anaerobic pretreatment and aerobic post-treatment remains therefore quite attractive with respect to the excess sludge production. In view of existing problems with the disposal of excess sludge in densely populated regions, this certainly is a factor of considerable importance, since the sludge exerts a fairly satisfactory "dewaterability." The 7.3-7.6 m^3 *methane gas* produced from the 72 m^3 of raw waste treated corresponds to 7.1-7.3 m^3 CH_4 $(PE)^{-1}$ $year^{-1}$. According to figures presented by Imhoff[13] for a primary + secondary aerobic treatment process combined with sludge digestion, approximately 9 m^3 biogas is produced (corresponding to 6.75 m^3 CH_4), which is slightly lower than the amount of methane gas produced in the direct anaerobic pretreatment of raw sewage.

However, depending on the temperature and the influent COD, 10-20% of the methane gas may be lost in dissolved form with the effluent solution. This loss of methane gas can be reduced by applying air stripping to the effluent solution for recovering the dissolved methane. The air used for the stripping operation can be applied afterwards for burning the biogas, e.g., for electricity production or for other purposes.

TABLE VII

Estimation of the Amount of Excess Sludge over the First 350 Days of the Experiment on the Basis of Influent COD Values of 19.1-21 kg and a sludge washout of 40 mg COD/L

Influent COD (mg/L)	Total COD supplied (kg)	COD reduction (%)	Total COD removed (kg)	COD-SS[a] washed out (kg)	CH_4-COD[B] (kg)	Estimated amount of excess sludge based on: COD (kg)	SS[c] (kg)	volume[d] (L)
525	37.8	75	28.4	2.9	19.1	6.40	4.8	96
525	37.8	75	28.4	2.9	21	4.35	3.26	65
500	36	75	28.4	2.9	19.1	4.40	3.30	66
525	37.8	72	27.2	2.9	19.1	5.20	3.90	68
500	36	72	25.9	2.9	19.1	3.90	2.90	58
525	37.8	72	27.2	2.9	21	3.30	2.50	50
550	39.6	75	29.7	2.9	19.1	7.70	5.80	116
525	37.8	78	29.5	2.9	19.1	6.40	4.80	96

[a]Based on an average sludge COD washout of 40 mg/L.
[b]The 21 kg CH_4-COD is based on 10% higher CH_4 production than the 19.1 kg CH_4-COD calculated from the volume of biogas produced.
[c]The 1 kg sludge-SS = 0.75 kg sludge COD.
[d]The SS content of the sludge is 5%.

Post-Treatment

Air stripping may represent the first post-treatment step not only for recovering of the dissolved biogas but also for removing dissolved volatile malodorous compounds, in order to prevent any nuisance to the environment. Since up to 80–90% of the biodegradable organic compounds have been eliminated in the anaerobic pretreatment step, it will be evident that the potentials of the effluent to produce new malodorous compounds are low as compared to the raw waste.

The environmental problems which might arise with respect to malodorous nuisance therefore can be attributed to dissolved compounds formed in the anaerobic pretreatment step. In our experience, the content of malodorous compounds in anaerobic effluent is rather small and presumably any serious environmental problems will not arise, even not if a separate air-stripping step is omitted. Since the dissolved end and intermediate products of the anaerobic step represent a class of highly reduced compounds, most of these are rapidly eliminated either chemically or biochemically in applying an aeration step. This has been checked in preliminary laboratory experiments with aerobic and microaerophilic (in which the oxygen concentration in the solution remains close to zero) post-treatment steps. Reduced S compounds are eliminated very rapidly in this manner. Therefore, any malodorous nuisance problems will not arise after the anaerobic effluent has been subjected to such a post-treatment step.

In those cases where restrictions are set for the disposal of reduced N compounds into receiving waters, it is evident that a significant part of the total oxygen demand of the waste water remains after the anaerobic treatment step, i.e., approximately 20% of the BOD, corresponding to 11 g 0_2 demand per PE (which is set at 54 g BOD/day) and 95% of the N oxygen demand (45 g 0_2 $(PE)^{-1}$ day^{-1}), corresponding to 43 g 0_2 $(PE)^{-1}$ day^{-1}. The NH_4^+-N can be removed by converting it to $N0_3^-$-N by nitrification but, in order to reduce the energy requirements of the treatment process, it would be very attractive if the nitrification process could be combined with a denitrification step for the elimination of the remaining BOD. Process schemes have been described for that purpose in the literature[14-17] and it has been shown that a USB reactor can also be beneficially applied in the denitrification step.

However, it will be evident that, with the amount of BOD still remaining after the anaerobically pretreatment of the wastewater, only a partial denitrification can be accomplished. A less complete BOD removal should be pursued in the anaerobic treatment in order to vaporize the bound oxygen in the NO_3^- more completely, but this will result in a lower biogas production, which might be even less beneficial. The policy followed in this respect greatly depends on the use that can be made of the biogas, the restrictions set for the disposal of NH_4^+, and the costs of disposal of NH_4^+-N into receiving waters, and obviously also the energy requirements of the nitrification step. It will be evident that for aerobic treatment systems with a low energy consumption, such as rotating disk processes, the value to be put on the oxygen bound in the

NO_3^--N is considerably lower than for conventional low loaded activated sludge processes. So far, little experience exists for treating these low BOD and high NH_4^+-N effluents[17] and additional research in this field—particularly as far as low-energy aerobic processes are concerned—should be stimulated. Preliminary experiments conducted with microaerophilic- and aerobic-activated sludge systems indicate that effluent BOD and COD values of a combined anaerobic-aerobic treatment process at least are as low as those obtained in a one-step low loaded activated sludge process.

Prospects of Anaerobic Treatment of Raw Sewage

In view of the results obtained in this investigation it may be concluded that anaerobic treatment of raw sewage in principle can be beneficially applied, even at temperatures as low as 8°C, once a sufficient amount of granular seed sludge has become available. In due time this certainly will be the case because, in the application of anaerobic treatment for various industrial wastes, a granular type of sludge can be cultivated. However, for the time being, digested sewage sludge should be used as seed, and at this time no information is available about the applicability of this sludge at temperatures below 11°C. Recent results obtained with digested sewage sludge as seed indicate that satisfactory results can be obtained at liquid detention times as low as 18–24 h and at temperatures exceeding ca. 15°C.[11] Presently running experiments indicate that appreciably lower detention times or temperatures can be tolerated, but exact information can not yet be provided. These larger pilot plant scale experiments also give more relevant information about the requirements to be set for the feed inlet system, at least for flocculant sludge. In view of the rather low organic space loads that can be applied in the treatment of dilute and relatively cold waste waters such as sewage, and, consequently, the lower mixing resulting from the gas production, it will be obvious that more feed inlet points should be installed than in the same reactor under high (i.e. over 10 kg COD m^{-3} day^{-1}) organic loading conditions. In the latter case, one feed inlet point per 5 m^2 suffices, although a secondary startup after a feed interruption will proceed slower than in reactors with a more homogeneous feed inlet distribution system. Presumably more feed inlet points will be required the denser is the sludge in the reactor, but so far no exact information is available. However, the results obtained in the 6-m^3 flocculant sludge bed reactor have shown that quite satisfactory results can be obtained with one feed inlet point per 2 m^2. With dense (i.e. granular) sludge bed systems this presumably is the minimum. Practical solutions for a simple full-scale UASB plant for treating raw sewage are shown in Figure 5.

In using granular sludge, a fluid bed operation such as that pursued in the AAFEB process might be considered. However, according to results recently obtained with dilute waste in a 2-m-high 12.7-L UASB reactor, a fluidized bed operation does not really look profitable.[18] The same results presumably can be obtained in a combined UASB-AF process, in which the settler compartment of the UASB reactor is packed with some proper support material,[19]

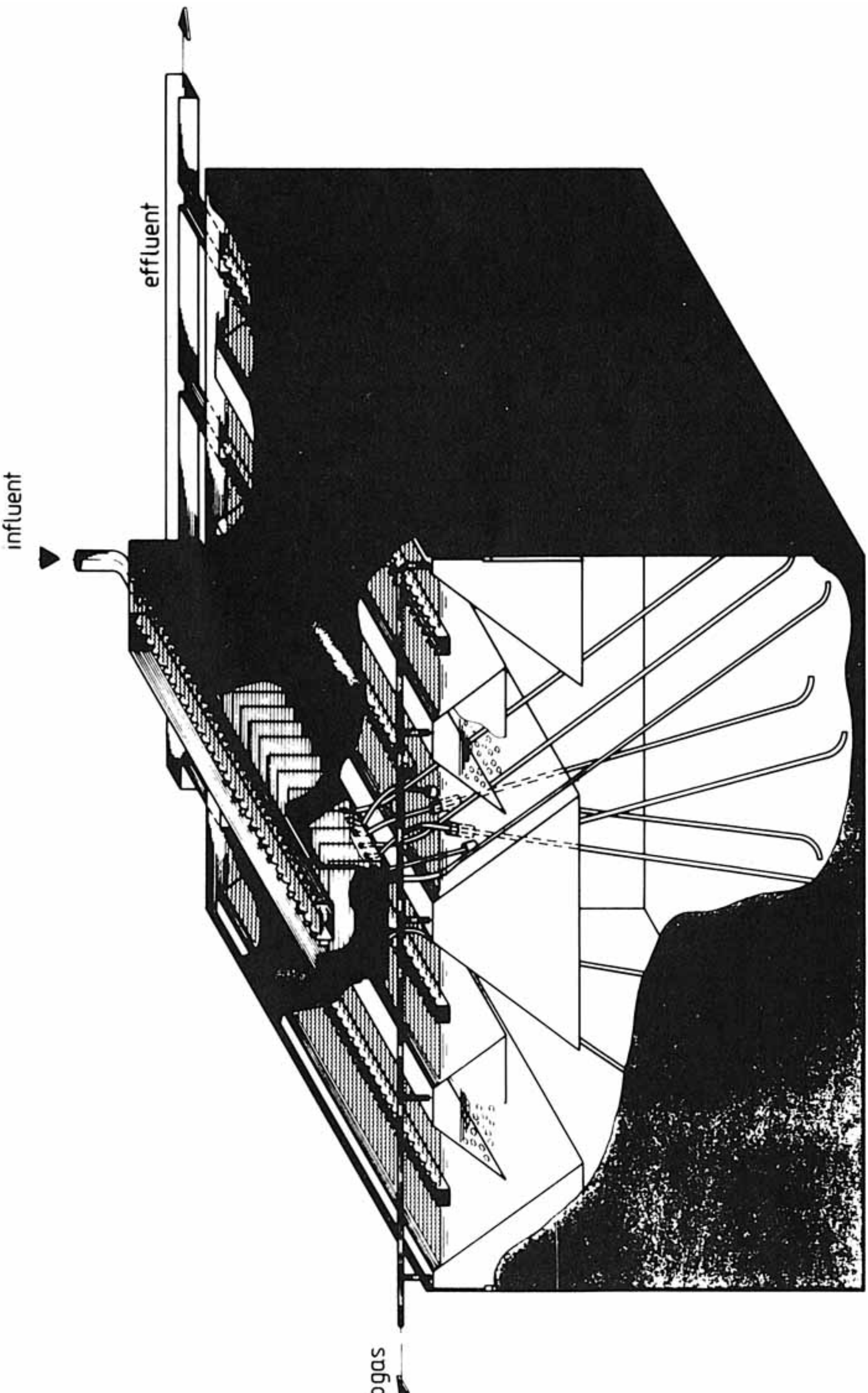

Fig. 5. A possible full-scale UASB plant treating raw domestic sewage.

as well as in the case that the UASB reactor would be equipped with a more sophisticated feed inlet distribution system, i.e. conforming to the systems required for fluidized bed systems.

Regarding the operation of a full-scale UASB plant for sewage, little if any insufferable problems are foreseen, provided the raw sewage is essentially free from any highly toxic compound at inhibitory concentration. In the two years of experiments with the raw domestic sewage of the village Bennekom, there was no clear evidence of any serious upset due to the presence of toxic compounds. However, this situation may be less favorable for sewage with a relatively high fraction of industrial waste.

The results indicate a lower treatment efficiency at very low COD influent values which occur from time to time in combined sewer systems. Insufficient results are available so far to allow a decision whether or not this drop in treatment efficiency can be prevented (or reduced) by applying a longer detention time. Considering the results obtained, it looks reasonable to design the process for storm weather situations at a hydraulic detention time of 24 h for granular seed sludge bed systems. However, more situations should be studied before definite conclusions can be drawn.

The use of granular seed sludge certainly is very attractive because, aside from its high specific activity, this sludge can be retained in the reactor for a long period of time. Practically all the excess sludge, which predominantly is flocculant in appearance, will accumulate above the granular sludge bed and can be discharged from time to time somewhere from the upper part of the reactor. A very attractive practical point of anaerobic pretreatment in UASB-reactors or other appropriate processes such as the anaerobic filter, undoubtedly is that the process can be applied at very large as well as very small scale. But above all the process is compact, simple, and inexpensive in investment and operational costs, which particularly may be a very attractive benefit for countries suffering from a lack in hard currency.

CONCLUSIONS

Anaerobic treatment of raw sewage using the UASB concept appears to be a realistic alternative for conventional aerobic treatment processes, although generally the anaerobic step should be followed by an aerobic treatment step. Anaerobic treatment is effective at temperatures from 8 to 10°C, provided a high-quality—preferentially a granular—seed sludge can be applied, consequently forming a granular sludge UASB reactor. So far, insufficient reliable data are available concerning the potentials of using digested sewage sludge as inoculum at temperatures below 10°C, but even the use of this type of seed sludge under these extreme temperature conditions should not be excluded, although the maximum organic and hydraulic loading rates may be two to three times lower than in granular sludge bed UASB reactor. However, at this stage of the research, even the maximum loading potentials of a granular sludge bed system still are greatly unknown. Based on the experimental results obtained so far in this study, the following conclusions can be drawn:

1) Under dry weather conditions 65–85% COD reduction can be achieved in treating raw domestic sewage at temperatures in the range 8–20°C and at hydraulic loads as high as 2 m^3 m^{-3} day^{-1}. Under wet weather conditions, the COD reductions generally are in the range 50–75% under the same temperature hydraulic loading conditions.

2) The excess sludge production in anaerobic treatment is in the range of 5.0–8.6 kg TS PE^{-1} $year^{-1}$, which is only 25–40% of that in a conventional aerobic treatment system combined with sludge digestion.

3) The methane production in anaerobic treatment of raw domestic sewage is in the range 7.1–7.3 m^3 CH_4 PE^{-1} $year^{-1}$. Based on the amount of COD removed, the average conversion to CH_4 COD is 71%.

4) Generally, the anaerobic treatment step should be followed by some adequate post-treatment in order to meet the restrictions set for discharge of effluents into receiving waters. As a first step, air stripping might be attractive for removing any volatile malodorous compounds and for removing (and recovering) dissolved methane gas.

5) Larger-scale experiments should be carried out to prove the feasibility of the process at a large scale and particularly in assessing a proper feed inlet distribution system for granular sludge bed reactors.

6) The UASB concept looks quite attractive for application to raw domestic sewage, because the process is simple, compact, and inexpensive.

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Nomenclature

AAFEB	anaerobic attached film expanded bed
AF	anaerobic filter
BOD	biochemical oxygen demand
BT	biolytic tank
COD	chemical oxygen demand
CT	contact tank
DS	dry solids
PE	population equivalent
TOC	total organic carbon
TS	total solids
TSS	total suspended solids
UASB	upflow anaerobic sludge blanket
VFA	volatile fatty acids
VS	volatile solids
VSS	volatile suspended solids
$\Delta sludge_{acc}$	amount of sludge accumulated in the reactor
$\Delta sludge_{AT}$	excess sludge production in anaerobic treatment

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