Influence of higher organic loading rates on the efficiency of an anaerobic hybrid digester while treating landfill leachate

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Abstract

An anaerobic hybrid laboratory-scale digester was used to evaluate the treatment efficiency when using high strength landfill leachate at organic loading rates (OLR) of more than 20 kg COD $m^{-3}{\cdot}d^{-1}$. The digester was operated at mesophilic temperatures and the hydraulic retention kept constant at 1,0 d. It was found that the digester can be used successfully to treat landfill leachate at higher OLRs and should be able to withstand loading shocks within specific values. The data showed that at an OLR of >24 kg COD$\cdot m^{-3}{\cdot}d^{-1}$, a total COD removal of 88% can be obtained with a CH_4 yield of 0,237 $m^3{\cdot}kg^{-1}$ COD removed. At an OLR of 26,05 kg COD$\cdot m^{-3}{\cdot}d^{-1}$ the hybrid digester could reduce the COD of the leachate by 95% and more than 80% at a loading rate of 29,0 kg COD $m^{-3}{\cdot}d^{-1}$. The methane content of the biogas varied between 64% and 74%. Total methane yields per COD removed ranged between 0,215 and 0,230 $m^3{\cdot}kg^{-1}$ COD at OLRs of 26,05 and 29,0 kg $m^{-3}{\cdot}d^{-1}$ respectively. The poor propionic acid removal of 68% at COD concentrations of 29,0 kg COD $m^{-3}{\cdot}d^{-1}$ appeared to be an indication of digester overloading and impending digester failure.

Introduction

Landfill-site dumping is one of the oldest and most common methods of municipal waste disposal and dates back as far as 6 000 to 3 000 BC. Since it appears to be financially and technically the most viable solution, landfilling is likely to remain the commonest method to treat municipal waste. Landfills are really just large bioreactors that generate 2 types of products, leachate and biogas, from aerobic and anaerobic refuse catabolism.

The most important aspect that must be taken into consideration is the capacity of landfills to generate leachate and particular attention must be paid to the protection of surface and ground waters. Leachate is water which has percolated through emplaced refuse, carrying with it soluble compounds and transportable organic and inorganic materials as well as bacteria and viruses. These pollute soil and ground water and decrease their value for man and beast. Various field observations indicate that even small municipal landfills may impact ground water (Bagchi, 1987). South Africa, a semi-arid country with limited water resources, cannot afford to lose water by unnecessary pollution. In many parts of the United States no new natural-attenuation landfills are permitted, so as to prevent ground-water pollution. Since many of the newly constructed landfills are sealed at the bottom, especially in Germany, Italy and the UK, leachate becomes an even greater problem and must be removed for treatment by physical-chemical or biological methods (Stegmann, 1983).

The collection and treatment of leachate are now recognised as 2 of the greatest problems associated with the operation of landfill sites. Anaerobic digestion is a promising possibility for the treatment of landfill leachate (Henry et al., 1987). Britz et al. (1990) found that a hybrid digester could reduce the chemical oxygen demand (COD) of leachate by 82% at a loading rate of 18,65 kg COD $m^{-3}{\cdot}d^{-1}$.

The objective of this study was to evaluate the treatment efficiency of an anaerobic hybrid digester, when using a COD concentration of more than 20 kg COD $m^{-3}{\cdot}d^{-1}$.

Materials and methods

Anaerobic digester

A laboratory-scale upflow anaerobic digester (hybrid) with a working volume of 5 ℓ was used in the study. The digester combined a fixed-film (an inert porous polyethylene foam fitted to the inside wall) and an upflow sludge blanket (Fig. 1). The leachate substrate was introduced continuously via a horizontal inlet at the base of the digester. Biogas exited at the top via a gas-solids separator and gas production was determined by means of an electronic gas-measuring system. The biogas volumes were corrected for standard temperature and pressure (STP) conditions. An operational temperature of 35°C was used and regulated by means of a heating tape

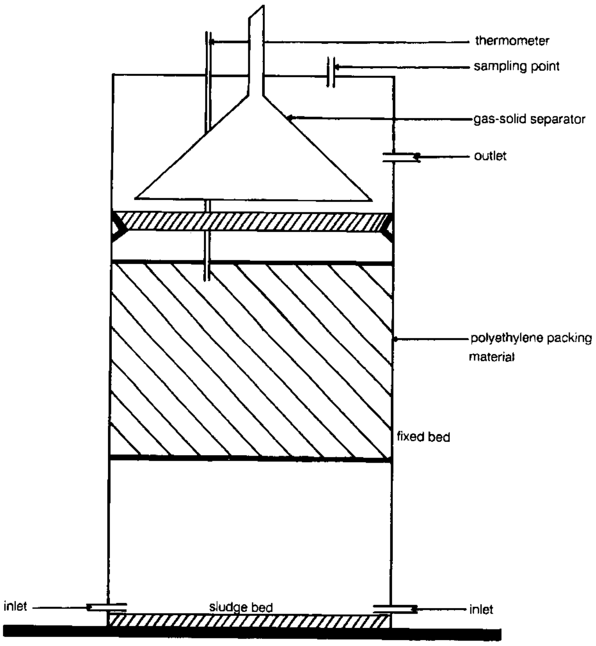

Figure 1
Laboratory-scale anaerobic hybrid digester

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TABLE 1
COMPOSITION OF THE RAW LEACHATE FROM THE DIFFERENT LANDFILL SITES

Parameters	[1]Coastal Park		[2]University of Cape Town		[3]Bloemfontein	
	minimum	maximum	minimum	maximum	minimum	maximum
COD (mg·ℓ^{-1})	200	30 700	27 300	36 700	<100	500
pH	7,75	8,88	7,6	8,32	7,78	8,02
TVFA (mg·ℓ^{-1})	150	20 000	9 83	15 733	ND	144
Acetic acid (mg·ℓ^{-1})	130	18 000	3 023	5 827	ND	70
Propionic acid (mg·ℓ^{-1})	0	4 100	1 554	2 400	ND	9
n-Butyric acid (mg·ℓ^{-1})	0	8 000	2 634	4 018	ND	26
Alkalinity (mg·ℓ^{-1})	750	12 066	6 997	11 745	ND	ND
TKN (mg·ℓ^{-1})	17	2 908	1 367	2 375	ND	ND
TS (mg·ℓ^{-1})	70	15 600	46 250	52 650	ND	ND
TNVS (mg·ℓ^{-1})	60	9 108	33 490	39 100	ND	ND
TVS (mg·ℓ^{-1})	10	6 492	12 760	13 550	ND	ND

1 Average of 10 batches
2 Average of 5 batches
3 Average of 4 batches

TABLE 2
AVERAGE COMPOSITION OF THE LEACHATE SUBSTRATE USED IN THIS STUDY*

Parameters	Phase 1	2	3	4
HRT (d)	1,0	1,0	1,0	1,0
Substrate pH	6,0	6,0	6,0	6,0
Loading rate (kg COD·m^{-3}·d^{-1})	21,65	24,1	26,05	29,0
COD (mg·ℓ^{-1})	21 650	24 100	26 050	29 000
TVFA (mg·ℓ^{-1})	11 837	14 870	9 964	14 863
Acetic acid (mg·ℓ^{-1})	4 420	5 441	3 674	5 329
Propionic acid (mg·ℓ^{-1})	1 762	2 142	1 421	2 317
Isobutyric acid (mg·ℓ^{-1})	200	265	174	243
n-Butyric acid (mg·ℓ^{-1})	5 139	6 576	4 403	6 563
n-Valeric acid (mg·ℓ^{-1})	46	68	45	41
Hexanoic acid (mg·ℓ^{-1})	270	379	248	370
Alkalinity (mg·ℓ^{-1})	1 343	1 667	4 900	1 869
TS (mg·10mℓ^{-1})	242	186	174	196
TNVS (mg·10mℓ^{-1})	150	99	96	107
TVS (mg·10mℓ^{-1})	92	88	77	89

* Mean values for four determinations

and temperature-sensitive controls (Meyer et al., 1983). The digester was originally seeded using a mixture of active laboratory sludge, municipal sewage and cells from an anaerobic cell generator. At the start, leachate with a COD of 7 000 mg·ℓ^{-1} was fed to the digester. The substrate flow rate was set at a hydraulic retention time (HRT) of 5,0 d. The HRT was gradually shortened to 1,0 d over a period of one month. The COD concentration was simultaneously increased stepwise to 18 900 mg·ℓ^{-1}. For the rest of the study the HRT was kept constant at 1,0 d with only the organic loading rate (OLR) being changed.

Experimental phases

The study consisted of 4 experimental phases (Phases 1 to 4) during which the OLR was increased from (in kg COD m^{-3}·d^{-1}): 21,65; 24,1; 26,05 to 29,0. Before each increase in OLR the digester was operated at "stable state" conditions for 7 HRTs. The latter was assumed when, after 5 volume turnovers, parameters showed a variation of less than 10%.

Leachate substrate

Leachate batches used in the study were obtained from the Coastal Park, UCT and Bloemfontein Municipal solid waste disposal sites. The leachate was in each case collected in 25 ℓ drums, transported to Bloemfontein and stored at 4°C until required. The different batches had a COD varying between 1 000 and 45 000 mg·ℓ^{-1}. To standardise the substrate, different batches of leachate were mixed to give the COD value required for each phase. Before use, additional nitrogen ($CO(NH_2)_2$ 100 $\text{mg}\cdot\ell^{-1}$) and phosphate (KH_2PO_4 100 $\text{mg}\cdot\ell^{-1}$) as well as a sterile trace element solution (Nel et al., 1985), were added. The pH was adjusted to 6,0 to optimise the environment for maximum bacterial growth. As a result of the varying leachate volumes and concentrations, it was necessary at certain times to supplement the raw leachate with a synthetic medium to obtain the required OLRs. The synthetic medium consisted of ($\text{g}\cdot\ell^{-1}$): glucose - 2,5; cellulose - 0,5; starch - 0,2; yeast extract - 0,2; peptone - 0,2; gelatin - 0,2; acetic acid - 4,7; propionic acid - 2,6; isobutyric acid - 0,4; n-butyric acid - 10,4; n-valeric acid - 0,1 and hexanoic acid - 0,5.

Analytical methods

The following parameters were monitored and analysed according to *Standard Methods* (1985): pH, COD, biogas production and composition, total solids (TS), total non-volatile solids (TNVS), total volatile solids (TVS), alkalinity, orthophosphate phosphorus ($P\text{-}PO_4$) and sulphate (SO_4).

Volatile fatty acids (VFA) were determined using a gas chromatograph (GC) equipped with a flame ionisation detector and a 30,0 m x 0,75 mm ID NUKOL capillary column. The chromatograph was programmed at an initial temperature of 120°C, then increased at a rate of $6°\text{C}\cdot\text{min}^{-1}$ to a final temperature of 185°C. The detector and the inlet temperatures were set at 250°C and 160°C respectively. Nitrogen was used as a carrier gas at a flow rate of 5 $\text{m}\ell\cdot\text{min}^{-1}$. Biogas composition was determined on a GC equipped with a thermal conductivity detector and column (2,0 m x 0,3 mm ID) packed with Porapak Q, 80-100 mesh. The oven temperature was set at 55°C and hydrogen used as carrier gas at a flow rate of 40 $\text{m}\ell\cdot\text{min}^{-1}$.

Results and discussion

Raw leachate

The average composition of 4 different batches of leachate received from the different landfill sites, is given in Table 1. The data clearly show the wide variation in parameter values, indicating the wide variation of the batches received. As a result of the wide variation in the composition of the different leachates received, it was decided to mix the different leachates to obtain a more uniform leachate substrate.

Substrate utilisation

A summary of the leachate substrate composition is given in Table 2. During the study period only the COD was standardised and the OLRs were as follows: 21,65; 24,1; 26,05 and 29,0 kg $\text{COD}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$. The digester was set at a constant HRT of 1,0 d and the leachate substrate pH adjusted to a value of 6,0. The large variations in the total fatty acids, acetic, propionic and n-butyric acids in the substrate composition for each phase are all indications of the extremely wide variation in the composition of the different leachates. Stable state conditions were used as criterion for increasing the OLR.

Table 3 shows the composition of the digester effluent during the 4 phases after stable state conditions were reached. The pH of the final digester effluent remained constant at about 8,0 during all 4 phases of the study, while the alkalinity increased sharply from Phase 1 onwards. According to Duff and Kennedy (1982), alkalinity plays an important role in minimising overloading effects.

TABLE 3
AVERAGE COMPOSITION OF THE REACTOR EFFLUENT USED DURING THIS STUDY*

Parameters	**Phase** 1	2	3	4
HRT (d)	1,0	1,0	1,0	1,0
Effluent pH	8,04	8,02	8,00	8,03
COD ($\text{mg}\cdot\ell^{-1}$)	2 500	3 000	1 300	4 500
TVFA ($\text{mg}\cdot\ell^{-1}$)	2 514	1 175	1 078	1 863
Acetic acid ($\text{mg}\cdot\ell^{-1}$)	994	520	438	763
Propionic acid ($\text{mg}\cdot\ell^{-1}$)	1 115	385	424	753
Isobutyric acid ($\text{mg}\cdot\ell^{-1}$)	77	38	36	55
n-Butyric acid ($\text{mg}\cdot\ell^{-1}$)	172	176	128	208
Isovaleric acid ($\text{mg}\cdot\ell^{-1}$)	19	4	5	9
n-Valeric acid ($\text{mg}\cdot\ell^{-1}$)	106	31	30	50
Hexanoic acid ($\text{mg}\cdot\ell^{-1}$)	30	21	17	26
Alkalinity ($\text{mg}\cdot\ell^{-1}$)	853	6 541	6 743	6 593
TS ($\text{mg}\cdot 10\text{m}\ell^{-1}$)	242	117	104	117
TNVS ($\text{mg}\cdot 10\text{m}\ell^{-1}$)	150	100	94	102
TVS ($\text{mg}\cdot 10\text{m}\ell^{-1}$)	35	17	10	16
Methane content (%)	77	74	74	64
Biogas yield ($\text{m}^3.\text{m}^{-3}$)	4,8	6,8	7,2	8,8

* Mean values for four determinations

In Fig. 2 the relationship between percentage COD removal and the COD removal rate (kg $\text{COD}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$) is illustrated. The removal rate (R-value) increased sharply during the first 3 phases, with the highest value being obtained during Phase 3. At both OLRs of 21,65 and 24,1 $\text{kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$, 88% COD removal was found, with 78% and 92% TVFA removals respectively (Fig. 3). The low TVFA removal during Phase 1 can partially be attributed to the low propionic acid removal of only 36%. Directly on changing the OLR it was usually found that the pH dropped slightly with increases in the isobutyric, butyric and propionic acid (HPc) concentrations in the digester effluent. Within 2 d the pH increased and stabilised at around 8,0 and the excess isobutyric and butyric acid disappeared. HPc was found to be the slowest parameter to stabilise after an increased organic loading.

The increase in volatile fatty acid levels as indicators of impending digester failure, has previously been intensively studied by Hill and his co-workers (Hill and Bolte, 1989). In a previous study with leachate as substrate (Britz et al., 1990), it was suggested that a decrease in HPc removal could possibly be used as an early indicator of digester overloading. According to Dohànyos et al. (1985), any change in technological parameters, such as organic loading, causes a simultaneous increase in the concentrations of all VFA, the highest being acetic and propionic acids. The slowest recovery and stabilisation are found in HPc. During Phase 1 of this study it could have been possible that a sufficiently large microbial population capable of degrading HPc, might not have accumulated to catabolise the high HPc concentrations present in the leachate substrate.

When the loading rate was increased to 26,05 kg $\text{COD}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$, an increase in COD removal (95%) was found. However, the TVFA removal decreased slightly to 89%. This was the best COD removal found during the whole study and can probably be ascribed to the lower TVFA in the substrate used during Phase 3.

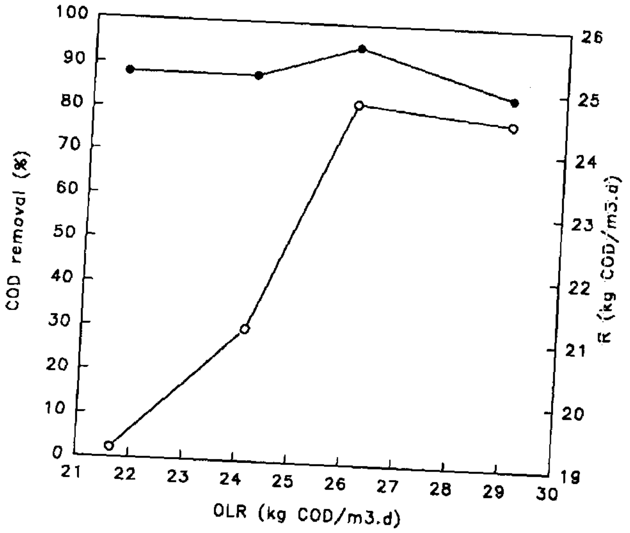

Figure 2
The effect of the increase in organic loading rate on the percentage COD removal (●) and the COD removal rate (R) (○)

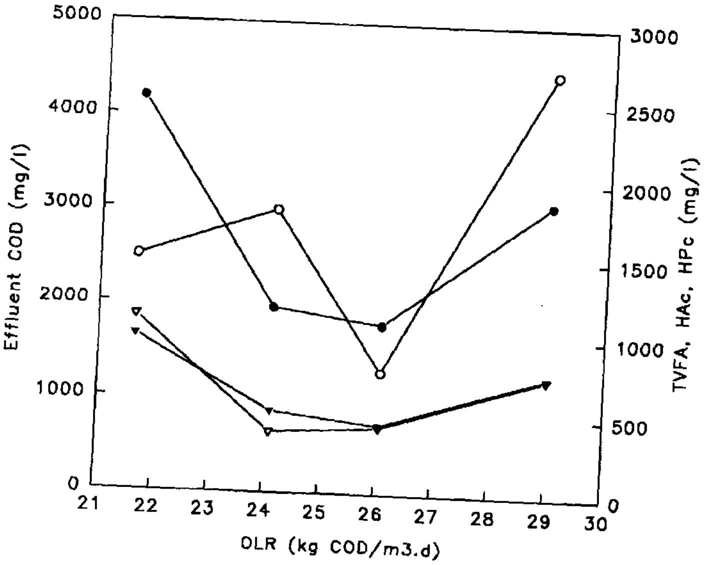

Figure 3
The effect of the increase in organic loading rate on the effluent COD (●), total volatile fatty acids (TVFA) (○), acetic acid (HAc) (▼) and the propionic acid (HPc) (▽) of the anaerobic hybrid digester

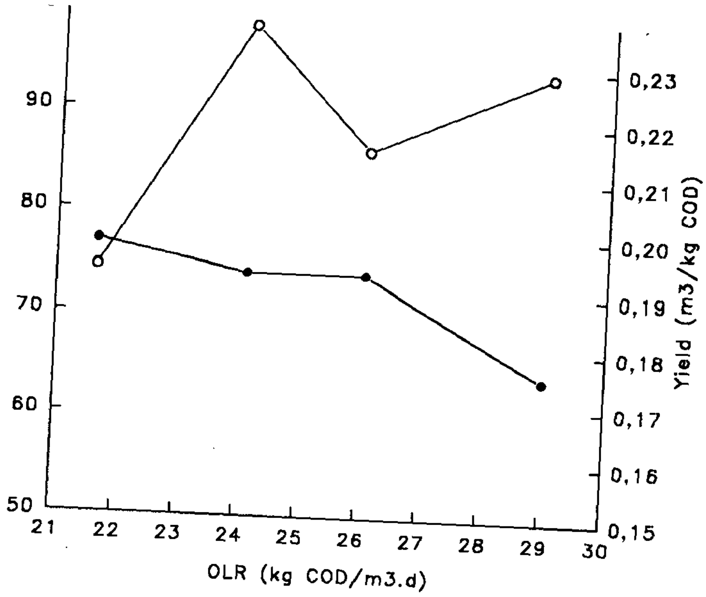

Figure 4
The effect of the increase in organic loading rate on the percentage methane content (●) and the methane yield (yield as m³ methane per kg COD removed (○)

During the final phase (29,0 $kg\cdot m^{-3}\cdot d^{-1}$), a decrease was found in both the COD removal (84,5%) and the TVFA removal (87,5%). This decrease in efficiency was seen as an indication that the digester was reaching its operational limits.

Effluent COD, pH and volatile acids

The effect of increases in the OLR on the digester effluent COD and the TVFA, acetate (HAc) and HPc remaining in the digester effluent for both digesters, is shown in Fig. 3. It was found, with the exception of Phase 3, that the effluent COD increased with increases in OLR. In the case of Phase 4 this represents an effluent COD value of 4 495 $mg\cdot\ell^{-1}$.

In contrast to the effluent COD values, the data showed that the TVFA decreased with increases in OLR with the exception of Phase 4 where the final effluent value was 1 932 $mg\cdot\ell^{-1}$. The best percentage TVFA and HAc removals were obtained during Phase 3 and this corresponds to the best COD removal rate during the same phase. In contrast the best HPc removal was obtained during Phase 2. However, it must be taken into consideration that in this study, volatile acid removal was based only on the influent value. Increases or decreases, resulting from the balance between genesis and trophy during the biomethanation processes, were not taken into consideration. Thus, it appears that at least half of the effluent COD is exerted by the un-utilised volatile acids.

Biogas production and composition

The biogas yield (Table 3) increased with the increase in OLR, with a final value of 8,8 $m^3\cdot m^{-3}$ at the OLR of 29,0 kg $COD\cdot m^{-3}\cdot d^{-1}$. The methane composition of the biogas as well as the methane yield during the 4 phases is illustrated in Fig. 4. From Phase 1 (21,65 kg $COD\cdot m^{-3}\cdot d^{-1}$) onwards, the methane content of the biogas decreased with increases in organic loading rate even though the biogas production increased with each phase (Table 3). The considerable decrease in methane content of the biogas during Phase 4 was especially striking. The methane content was thus affected by the higher OLR. Asinari Di San Marzano et al. (1981) reported that situations where HAc and HPc concentrations kept building up eventually led to a decrease in the methane production rate. Even slight changes in environmental conditions would result in thermodynamically unfavorable accumulation of dihydrogen and would shift the fermentative bacteria from the acetate plus dihydrogen pathway to the fatty acid pathway. These volatile fatty acids will accumulate in the effluent because of the absence of appropriate levels of obligate proton-reducing bacteria.

The methane yield in terms of the COD removed remained fairly constant. There was, however, a decrease in the methane yield (COD removed) at an OLR of 26,05 kg $COD\cdot m^{-3}\cdot d^{-1}$. This can be explained in terms of the relatively small increase in biogas formation from Phase 2 to Phase 3 (2 ℓ), while the increase in COD removal was 7%. The best observed methane production yield was obtained during Phase 2 at an OLR of 24,1 kg $COD\cdot m^{-3}\cdot d^{-1}$. During the whole study the methane production rates were much lower than the theoretical optimum of 0,395 $m^3\cdot kg^{-1}$ COD removed at 35°C for glucose. The values obtained in this study represent 49%, 60%, 54% and 58% recovery of energy values from the substrate used. However, it must be taken into consideration that the substrate used in this study was the effluent of a landfill site and the composition makes it extremely difficult to compare to an easily degradable substrate like glucose. It is also known that leachate contains many carbon sources that are generally difficult for the microbial communities to metabolise (Senior, 1986).

Conclusions

The production of leachate at landfill sites may continue for many years even after the landfill site has ceased operation (Lema et al., 1988). This fact must be taken into consideration when sites are planned or closed. In the literature it has been shown that anaerobic treatment can be used successfully and economically to treat leachate. However, anaerobic digestion has long been thought to be too slow, unreliable and sensitive to loading shocks (Young et al., 1987) to be used as a treatment option. The data from this study demonstrate that the anaerobic hybrid digester can successfully be used to treat landfill leachate at higher OLRs and should be able to withstand loading shocks within specific values.

The data also show that at an HRT of 1,0 d and an OLR of >24 kg $COD\cdot m^{-3}\cdot d^{-1}$, a total COD removal of 88% can be obtained with a CH_4 yield of 0,237 $m^3\cdot kg^{-1}$ COD removed. Organic loading rates of 29,0 kg $COD\cdot m^{-3}\cdot d^{-1}$ and an HRT of 1,0 d resulted in a COD removal of 84% and a CH_4 yield of 0,230 $m^3\cdot kg^{-1}$ COD removed. The study also showed that depending on the composition of the leachate even higher efficiencies (95% COD removal) can be obtained (Phase 3).

After continuous operation over a year, the hybrid anaerobic digester used in the study showed no obvious signs of clogging. However, a post-treatment will have to be undertaken before final disposal, in order to further reduce the level of organic matter to conform to local standards.

Acknowledgements

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References

ASINARI DI SAN MARZANO, C-M, BINOT, R, BOL, T., FRIPIAT, J-L, HUTSCHEMAKERS, J, MELCHIOR, J-L, PEREZ, I, NAVEAU, H and NYNS, E-J (1981) Volatile fatty acids, an important state parameter for the control of the reliability and the productivities of methane anaerobic digestions. *Biomass* **1** 47-59.

BAGCHI, A (1987) Natural attenuation mechanisms of landfill leachate and effects of various factors on the mechanisms. *Waste Manage. Res.* **5** 453-464.

BRITZ, TJ, VENTER, CA and TRACEY, RP (1990) Anaerobic treatment of municipal landfill leachate using an anaerobic hybrid digester. *Biol. Wastes* **32** 181-191.

DOHàNYOS, M, KOSOVA, B, ZABRANSKA, J and GRAU, P (1985) Production and utilization of volatile fatty acids in various types of anaerobic reactors. *Water Sci. Technol.* **17** 191-205.

DUFF, SJB and KENNEDY, KJ (1982) Effect of hydraulic and organic overloading on thermophilic downflow stationary fixed film (DSFF) reactor. *Biotechnol. Lett.* **4** 815-820.

HENRY, JG, PRASAD, D and YOUNG, H. (1987) Removal of organics from leachates by anaerobic filter. *Water Res.* **21** 1395-1399.

HILL, DT and BOLTE, JP (1989) Digester stress as related to iso-butyric and iso-valeric acids. *Biol. Wastes* **28** 33-37.

LEMA, JM, MENDEZ, R and BLAZQUEZ, R (1988) Characteristics of landfill leachates and alternatives for their treatment: A review. *Water Air Soil Poll.* **40** 223-250.

MEYER, LC, HUGO, AB, BRITZ, TJ, DE WITT, B and LATEGAN, PM (1983) Temperature control for laboratory-scale anaerobic digesters.

Water SA **9** 79-80.

NEL, LH, BRITZ, TJ and LATEGAN, PM (1985) The effect of trace elements on the performance efficiency of an anaerobic fixed film reactor treating a petrochemical effluent. *Water SA* **11** 107-110.

SENIOR, E (1986) Landfills : The ultimate anaerobic bioreactor. In: *Proc. 1st Anaerobic Digestion Symposium.* Bloemfontein, South Africa. 230-242.

STANDARD METHODS (1985) *Standard Methods for the Examination of Water and Wastewater* (16th edn.) American Public Health Association, Washington, DC.

STEGMANN, R (1983) New aspects on enhancing biological processes in sanitary landfill. *Waste Manage. Res.* **1** 201-211.

YOUNG, CP, BLAKEY, NC and MARIS, PJ (1987) Leachate management. In: *Proc. Harwell Landfill Practical Symposium.* Harwell, Oxon, UK. 47-56.