Performance of and biomass characterisation in a UASB reactor treating domestic waste water at ambient temperature

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Abstract

Domestic waste water from the city of A Coruña (NW Spain) was treated anaerobically in a laboratory-scale upflow anaerobic sludge blanket (UASB) digester, at 20°C, at hydraulic retention times (HRTs) of longer than 24 h, the COD and SS removal efficiencies remained practically constant and higher than 85%. When reducing the HRT from 24 to 5 h, the COD removal decreased from 85% to 53% and the SS removal from 89% to 63%. The methane recovered in the biogas ranged from 25% to 30% of the influent COD, increasing slightly with the operational time.

Methanogenic activities greater than 0.1 g CH_4-COD·g^{-1}VSS·d^{-1} were found for the sludge from the lower part of the UASB digester. The average methanogenic activity of the sludge decreased from 0.32 at the start-up to about 0.03 g CH_4-COD·g^{-1}VSS·d^{-1} at the end of operation, while the average sludge concentration was in the range of 8 to 10 g VSS·ℓ^{-1}. The amount and the methanogenic activity of the developed anaerobic sludge appeared to be the main efficiency-limiting factor of the UASB performance.

The removal efficiencies were increased by about 5% when the UASB digester was used in combination with a completely mixed sludge digester (CMSD) system for the external digestion and stabilisation of the accumulated solids into the UASB. This also led to the increase of the biomass concentration and uniformisation of the UASB sludge bed, but the average methanogenic activity remained low.

Nomenclature

BOD	Biochemical oxygen demand
CMSD	Completely mixed sludge digester
COD	Chemical oxygen demand ($_t$ total; $_s$soluble)
HRT	Hydraulic retention time
OLR	Organic loading rate
rCH_4	Methane production rate
SS	Suspended solids
SRT	Solids retention time
UASB	Upflow anaerobic sludge blanket
VFA	Volatile fatty acids
VS	Volatile solids
VSS	Volatile suspended solids
$\%COD_r$	Percentage COD removal
%M	Percentage COD converted into methane
$\%SS_r$	Percentage SS removal

Introduction

Directive 91/271/CE of the Council of Europe (1991) establishes efficiencies required for urban waste-water treatment installations in the near future. In terms of the objectives promulgated, 70 to 90% of BOD, 75% of COD and 90% of SS should be removed before discharching effluents in normal areas. On the other hand, the maximum treated effluent concentrations should be set to 25 mg BOD·ℓ^{-1}, 125 mg COD·ℓ^{-1} and 35 mg SS·ℓ^{-1}. Compliance with these criteria implies the construction of new treatment facilities in some countries, with the need for new, economic and efficient treatment methods.

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Received 11 September 1997; accepted in revised form 18 February 1998

Anaerobic digestion has become the most frequently used method for the treatment of medium-and high-concentration effluents, due to the economy of the process, and the low generation of surplus sludge. Different anaerobic technologies have been applied to the treatment of low-concentration effluents, like domestic waste waters, providing good treatment efficiencies at low or very low HRTs. The anaerobic fluidised bed or the expanded granular sludge bed reactors, with HRTs of about 2 to 4 h (Sanz and Fernández-Polanco, 1989, 1990; Van der Last and Lettinga, 1992) and the UASB reactor, with an HRT of 4 to 8 h (Vieira and Souza, 1986; Lettinga et al., 1980, 1993; Schelinkhout, 1993) offer the best results, while the anaerobic filter needs a longer HRT. On the other hand, the UASB reactor is the most frequently used reactor in full-scale installations for the anaerobic treatment of domestic waste waters but, at the moment, it is largely restricted to countries with a warm climate (Lettinga and Hulshoff Pol, 1991).

In the UASB process, waste water flows through a sludge bed (granular or flocculent), where different physical and biochemical mechanisms act in order to retain and biodegrade organic substances. Readily biodegradable substances are quickly acidified and then converted into methane and other biogas components. Solubilisation and hydrolysis of SS and macromolecules is a slow process accomplished by extracellular enzymes excreted by acidogenic bacteria (Gujer and Zenhder, 1983). As diluted waste waters should be treated at short HRTs and often are at ambient or low temperatures, complex substrates could leave the digester before being biodegraded. In UASB systems, the sludge bed acts as a filter to the SS, thereby increasing their specific residence time. In this way, the UASB reactor may achieve high COD and SS removals at very short HRT.

However, the accumulation of SS and adsorbed soluble organic matter in the sludge bed may provoke the displacement of active cells, leading to the formation of a sludge with a very low methanogenic activity. Also the accumulation of toxic or inhibi-

tory substances present in domestic waste waters could contribute to the loss of methanogenic activity of the sludge. However, little attention has been paid to the quality and characterisation of biomass developed in UASB digesters treating domestic waste waters.

The objective of this work was to study the anaerobic treatment of a municipal (domestic) waste water in a UASB digester, at ambient temperature. Special attention was paid to the accumulation and characterisation of active and inactive biomass in the digester. In an attempt to improve biomass quality and system efficiency, a modification of the UASB process was proposed and evaluated.

Materials and methods

Waste waters

Domestic waste waters were collected from a main sewer of the city of A Coruña, into the urban area. Waste-water samples were analysed for physico-chemical parameters after passing them through a 1 mm sieve, and then used for the continuous biological treatment. The feedstock was kept at 4°C, and renewed weekly.

Biomass

The anaerobic sludge used as seed for both continuous and batch assays was a mixture of three mesophilic sludges obtained from anaerobic digesters treating primary and activated sludge, fish canning waste water and sugar waste water. The sludge mixture had a concentration of 89.7 g SS·ℓ^{-1} and 31.9 g VSS·ℓ^{-1}, and a methanogenic activity of 0.32 g CH_4-COD·g^{-1} VSS·d^{-1} at 20°C and 0.75 g CH_4-COD·g^{-1} VSS·d^{-1} at 35°C.

Anaerobic reactor

A 2 ℓ active volume UASB reactor was used, located in a thermostat-controlled chamber at 20°C. Four lateral ports allowed samples to be taken of the digester content. A solid/liquid/gas separator was present in the upper zone of the reactor. The biogas was monitored with a continuous lab-scale gas flow meter (Veiga et al., 1990). The UASB was fed directly with the raw domestic waste water. In a second part of this study, the UASB reactor was operated in combination with a CMSD. The CMSD was fed with the mixed liquor drawn from the UASB reactor (where part of non-biodegraded influent solids accumulated),and an equal volume of the CMSD content was returned to the lower port of the UASB. The 1.6 ℓ active volume CMSD, was mechanically stirred and located in a thermostat-controlled bath at 35°C. This temperature was chosen in order to increase the biodegradation rate of the accumulated organic matter. The daily methane production from the CMSD was monitored with a liquid displacement system containing an alkaline solution. The VS content for the CMSD influent and effluent was also determined. The reactor configurations are shown in Fig. 1.

Batch biological assays

Methanogenic activity assays were carried out in 100 mℓ serum bottles as described previously (Soto et al., 1993). A stock solution of VFAs, previously neutralised with NaOH, was used as substrate feed; concentration in the assay medium was 3.8 g COD·ℓ^{-1} (2.0 g·ℓ^{-1} of acetic acid, 0.5 g·ℓ^{-1} of propionic acid and 0.5 g·ℓ^{-1} of n-butyric acid). The seed sludge concentration used in anaerobic assays was in the range of 1 to 3 gVSS·ℓ^{-1}. The methane production was measured by the displacement of an alkaline solution contained in Mariotte flasks (20°C).

The anaerobic biodegradability or potential methane production from solids accumulated in the UASB was determined. The biodegradability assay was carried out in 500 mℓ serum bottles following the same procedure as for the methanogenic activity test, but without VFA substrate addition. A control assay was performed in parallel in order to determine the methane potential of the seed sludge.

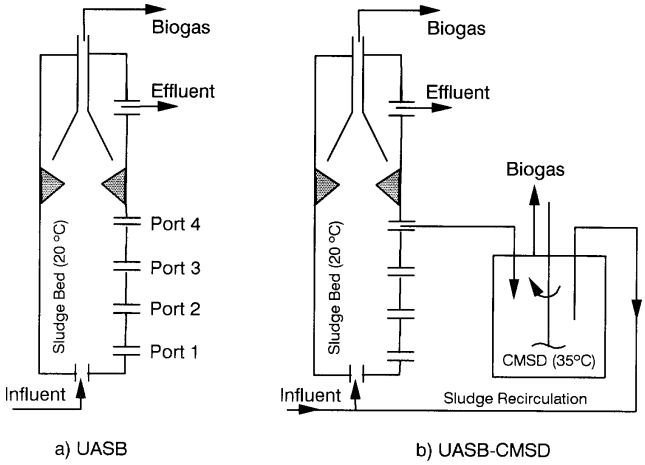

Figure 1
Schematic diagrams of experimental set-up

TABLE 1
DOMESTIC WASTE-WATER CHARACTERISTICS*

Parameter	Interval	Average value**
pH	6.95-8.3	7.8
CODt	220-985	693
CODs	63-523	322
BOD_5	250-640	360
SS	116-424	226
VSS	90-336	191
Fats	57-199	100
SO_4^{2-}	2.1-145	38.5
P-PO_4^{3-}	0.58-9.6	5.5
N-NH_3	2-34	20
TKN	9.5-65	38
Alkalinity	54-902	281

* Units in mg·ℓ^{-1}, except Alkalinity (in mg $CaCO_3$·ℓ^{-1}) and pH
** Average based in all influents used

Analytical methods

Determination of SS, VSS, CODt, CODs (filter paper size 1.2 μ), fats, orthophosphates and sulphates was carried out as recommended by *Standard Methods* (1992). Total Kjeldahl nitrogen (TNK) was determined by sample digestion with sulphuric acid and the selenium reagent, followed by sample distillation and

titration with chloride acid in a Kjeldahl apparatus (Bücki). Ammonia was determined by using an ion-selective electrode (Crison type 15230 3000). Gas composition was analysed by gas chromatography(HP 5890 serie II), using a thermal conductivity detector.

Results

UASB operation

The UASB reactor was inoculated with 1 ℓ anaerobic sludge. The start-up was initiated by feeding a synthetic waste water containing nutrients and 1 g·ℓ^{-1} of glucose as carbon source for a period of 15 d. Next, the influent was changed to domestic waste water, fed at low OLR to allow sludge adaptation to the waste water. The main characteristics of the domestic waste water fed to the UASB digester are presented in Table 1.

The UASB operation was divided into two main steps, separated by a shutdown time of 58 d. During the two steps, the OLR was increased progressively up to 3 g COD·ℓ^{-1}·d^{-1}, by increasing the flow rate which decreased the HRT down to 5 h. The HRT, the influent OLR applied to the system and influent and effluent COD and SS during the operational time are shown in Fig. 2, while the biogas production and the reactor efficiency parameters are shown in Fig. 3. The pH in the reactor was kept at 7±0.1 for the overall operation period, without addition of chemicals.

During this operational period, the influent COD ranged from 276 to 926 mg·ℓ^{-1}, with an average value of 696 mg·ℓ^{-1}. Similarly, the influent SS ranged from 116 to 336 mg·ℓ^{-1}, with an average value of 210 mg·ℓ^{-1}. The influent with the lowest COD and SS was fed during Periods III and VI. During these periods the effluent load was also lower, maintaining a constant global performance and improving the effluent quality. During Period III, the %M decreased continually. However, during Period VI, the %M increased noticeably, indicating that the biodegradation of part of the COD accumulated in the digester accounted for the overall methane production. During Periods VII to IX the OLR continued increasing, reaching about 3 g COD·ℓ^{-1}·d^{-1} at 5 h HRT. During these periods the UASB digester seems to accommodate adequately the hydraulic and organic shocks, as can be seen in Fig. 2.

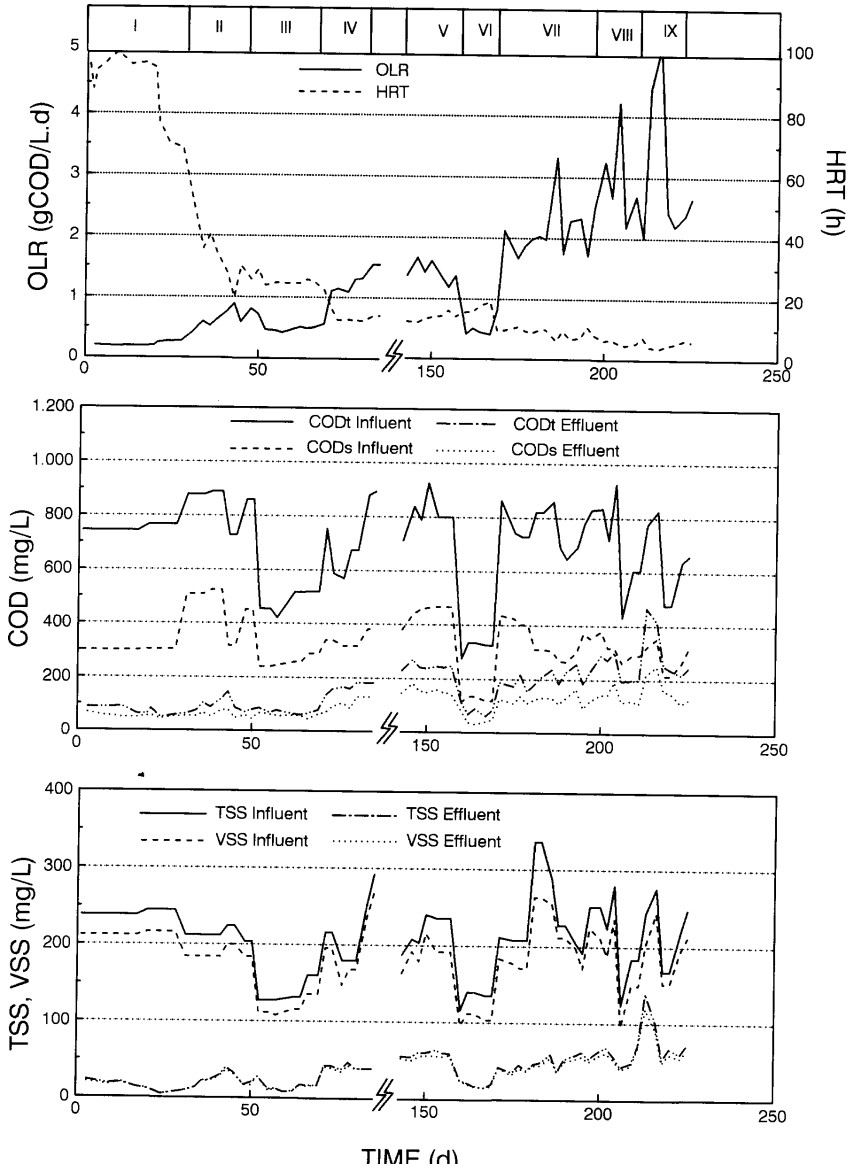

Figure 2
Operational parameters for the UASB reactor

The average methane content of the biogas obtained was 80%. The methane production recovered in the gas phase reached 0.20 ℓ CH_4·ℓ^{-1}·d^{-1} at the maximum OLR applied (Period IX). Part of the methane produced left the digester solubilised into the liquid phase. When this methane was accounted for, at the rate of 28.4 mℓ CH_4·ℓ^{-1} effluent (Perry and Chilton, 1973) (for a methane content of 80% in the gas phase), the overall methane production reached 0.34 ℓ CH_4·ℓ^{-1}·d^{-1}, giving an average value of 72 mℓ CH_4·ℓ^{-1} waste water.

The treatment efficiency, measured as COD and SS per cent removal, and the per cent COD converted into methane (%M) are shown in Fig. 4 as functions of HRT. Above an HRT of 24 h, the COD and SS removal efficiency remained practically constant and higher than 85%. The digester efficiency decreased progressively; when progressively lowering the HRT down to 5 h, the COD removal decreased to 53% and the SS removal to 63%. The %M ranged from 25% to 30% of the influent COD, increasing slightly with time. This fact may be explained by the accumulation of part of the influent VSS into the UASB, that were slowly but progressively solubilised and converted into methane.

Figure 4 also shows the distribution between soluble and suspended fractions for the COD remaining in the effluent. Both COD fractions followed a similar pattern with change of HRT. Data from Period VI (HRT=15.5 h) clearly show that low influent COD and SS improved the effluent quality, but reduced the

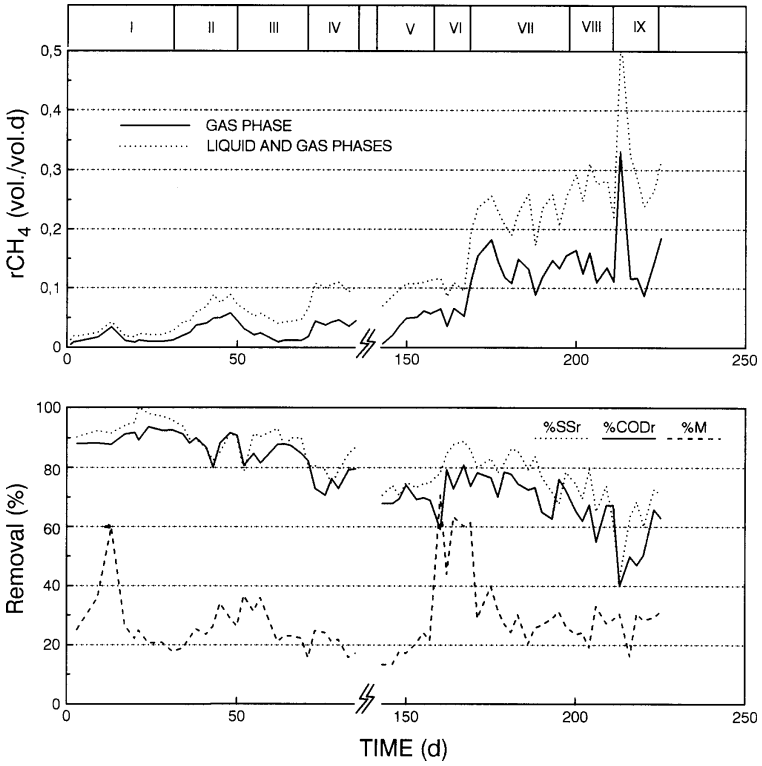

Figure 3
Efficiency parameters and methane production for the UASB reactor

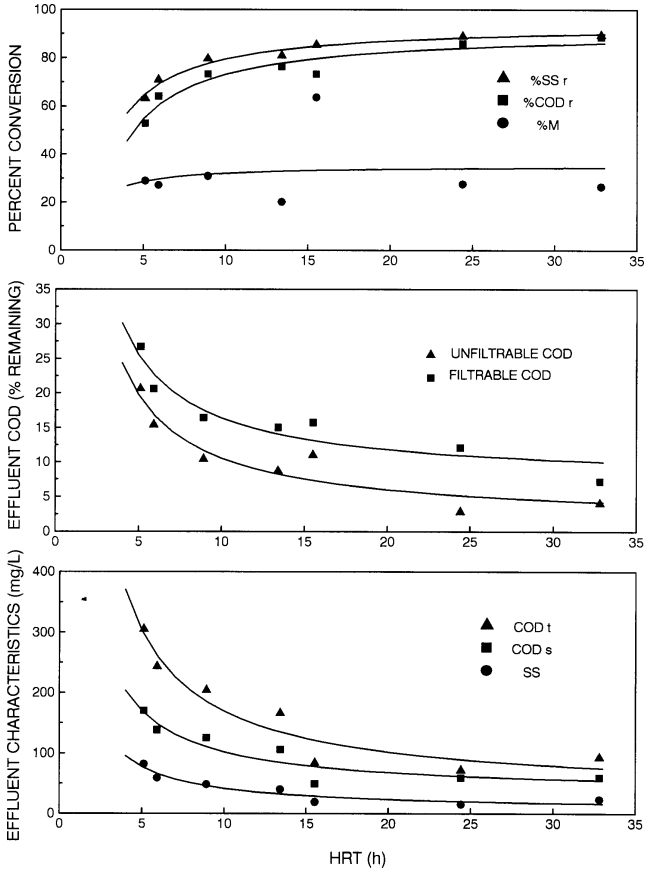

Figure 4
Efficiency and conversion parameters as a function of HRT

treatment efficiency slightly, when reported as percent COD and SS removed.

The feeding was stopped for 58 d between Periods IV and V, when the reactor had reached an HRT of about 13 h and an OLR of 1.3 g COD·ℓ^{-1}·d^{-1}. The reactor was restarted with the same conditions of hydraulic and organic load. Although the performance of the UASB reactor immediately after the restart-up did not differ substantially from that achieved previously, regarding methane prodution the system needed about 10 d to reach steady state.

Characterisation of the biomass accumulated in the UASB digester

The behaviour of the sludge bed in the reactor was analysed by taking sludge samples from different level ports. The results are presented in Table 2. The methanogenic activity of the sludge decreased from 0.32 g CH_4-COD·g^{-1} VSS·d^{-1} for the inoculum to 0.11 g CH_4-COD·g^{-1} VSS·d^{-1} after 85 d of operation (Period IV). After the shutdown time of 58 d, the methanogenic specific activity of the sludge from Port 2 had decreased to 0.064 gCH_4-COD·g^{-1}VSS·d^{-1} (Period V, day 143), but recovered and reached the value of 0.12 g CH_4-COD·g^{-1} VSS·d^{-1} at the end of the second operation step (Period VIII, day 210).

Further, the remaining methane potential (or anaerobic biodegradability) of the solids accumulated in the digester was determined. Samples of mixed liquor from the different ports of the UASB digester were taken during Period IX and subjected to biodegradability assays. Batch assays were performed at 20 and 30°C, in order to investigate the influence of temperature on the rate and extent of methane recovery. The same amount of VSS (2 g·ℓ^{-1}) from the UASB digester was used in all biodegradability assays. All the assays were carried out without adding seed sludge, except in the assay with the sample from Port 4, because the SS from this port did not show methanogenic activity. The results obtained are shown in Fig. 5. The rCH_4 at 30°C was about double that at 20°C.

The highest methane production was obtained with mixed liquor from the bottom and the upper zones of the UASB, and the minimum from the middle zone. At 30°C, the amount of methane recovered from the UASB sludge was about 250 (Port 1), 50 (Port 2), 75 (Port 3) and 125 (Port 4) mℓ CH_4 g^{-1} VSS.

Comparing these results with data in Table 2, it was observed that the accumulated organic matter at the upper zone of the UASBwas significant, but was not converted to methane, as the methanogenic activity of VSS in this zone was very low or zero. Therefore, recirculation or external digestion of the accumulated organics in the upper zone of the UASB would be necessary in order to achieve complete anaerobic stabilisation of waste-water components. External digestion in a CMSD was studied, the results being described in the following section.

TABLE 2
BIOMASS CONCENTRATION AND METHANOGENIC ACTIVITY (ACT) AT DIFFERENT LEVELS OF THE UASB REACTOR

Port	P1 (0)			P2 (8.5)			P3 (15.5)			P4 (22.5)		
Period	SS	VSS	ACT	SS	VSS	ACT	SS	VSS	ACT	SS	VSS	ACT
I	89.7	31.9	0.320	89.7	31.9	0.320	89.7	31.9	0.320	0.0	0.0	n.d.
IV	n.d.	n.d.	n.d.	74.5	26.6	0.113	38.2	15.4	0.093	0.0	0.0	n.d.
V	n.d.	n.d.	n.d.	54.9	21.8	0.064	13.8	6.6	0.026	0.0	0.0	n.d.
VIII	15.3	9.2	0.074	6.2	3.0	0.116	37.8	20.0	0.035	41.0	23.1	0.0

Units: SS and VSS in $g \cdot \ell^{-1}$; ACT in g CH_4-COD$\cdot g^{-1}$ VSS$\cdot d^{-1}$

TABLE 3
BIOMASS CONCENTRATION AND METHANOGENIC ACTIVITY (ACT) AT DIFFERENT LEVELS OF DE UASB REACTOR OPERATED IN COMBINATION WITH THE CMSD SYSTEM

Port	P1 (0)			P2 (8.5)			P3 (15.5)			P4 (22.5)		
Period	SS	VSS	ACT	SS	VSS	ACT	SS	VSS	ACT	SS	VSS	ACT
XII	30.5	20.0	0.027	50.4	25.3	0.028	55.6	30.4	0.010	36.9	20.3	0.015
XIV	33.2	22.2	0.012	27.9	17.8	0.014	33.5	20.6	0.020	41.0	23.8	0.017

Units: SS and VSS in $g \cdot \ell^{-1}$; ACT in g CH_4-COD$\cdot g^{-1}$ VSS$\cdot d^{-1}$

The UASB-CMSD operation and performance

A second experimental study was planned in order to assess the performance and operation characteristics of the combined UASB-CMSD system. The experimental set-up is shown in Fig. 1b. The UASB digester was operated at 20°C, between 6 to 7 h of HRT and 2 to 3 gCOD$\cdot\ell^{-1}\cdot d^{-1}$ of OLR. Domestic waste waters fed to the UASB digester during this period contained about 690 mg COD$\cdot\ell^{-1}$ and 244 mg SS$\cdot\ell^{-1}$.

The CMSD was inoculated with 0.5 ℓ of anaerobic sludge and operated at 35°C, because higher conversion rates for both hydrolytic and methanogenic steps were expected at this temperature than at ambient (20°C) temperature. The digester was operated without feeding for a week, in order to exhaust the biodegradable COD remaining in the sludge seed. Next, a volume of 0.2 ℓ mixed liquor from the top of the UASB digester was drawn and fed into the CMSD twice a week. An equal volume of mixed liquor from the CMSD was returned to the UASB digester at the lower port. The HRT and the SRT of the CMSD were both maintained at 28 d.

The biomass characteristics and distribution in the UASB digester during this period are shown in Table 3. The operation of the CMSD in combination with the UASB led to the uniformisation of the sludge bed in the UASB, increasing the VSS concentration at all levels, but decreasing the methanogenic activity, the latter probably due to the inhibitory effect of the mixed liquor from the top of the UASB being recirculated through the CMSD .

The conversion parameters for the combined UASB-CMSD system are shown in Fig. 6. The total COD and SS removals were increased up to 76% and 86%, respectively, at an HRT of 6.2 h and an OLR of 2.3 g COD$\cdot\ell^{-1}\cdot d^{-1}$.

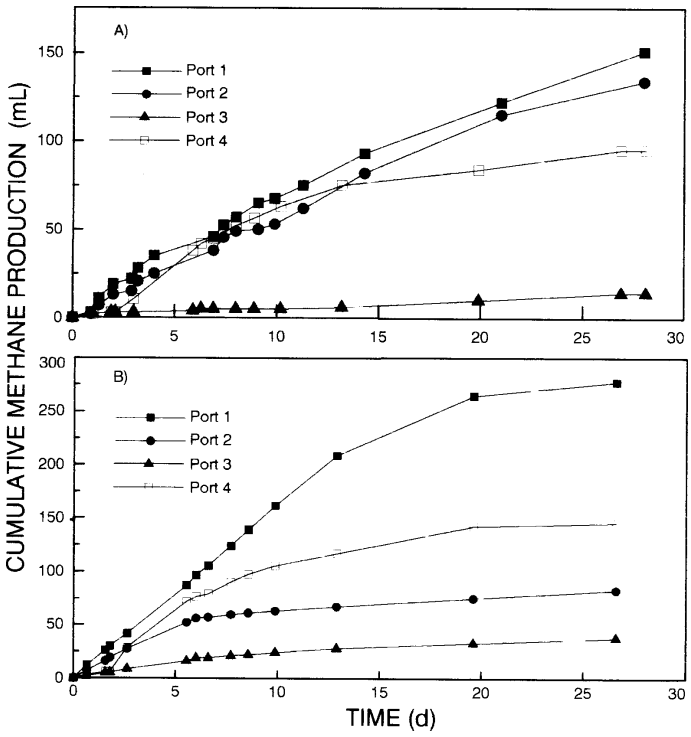

Figure 5
Cumulative methane production during biodegradability batch assays for the UASB mixed liquor (A: 20°C assays; B: 30°C assays)

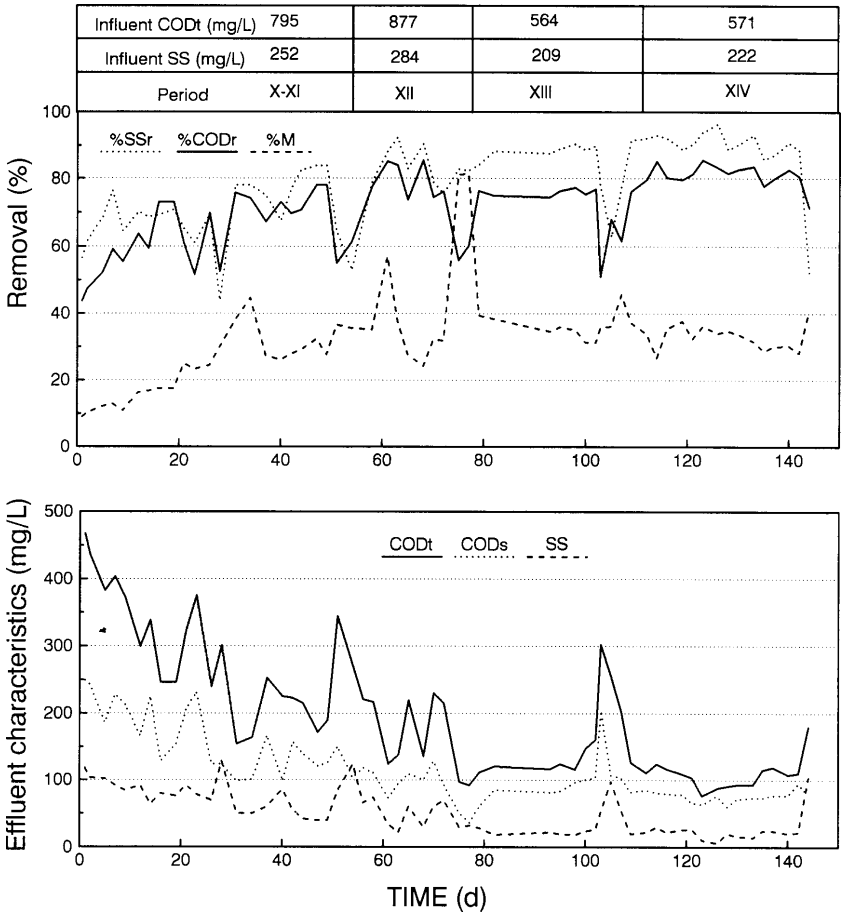

Figure 6
Operational parameters for the UASB-CMSD system

TABLE 4
BIOMASS CHARACTERISTICS FOR THE UASB REACTOR

System	Period	Average biomass concentration SS	VSS	Average methanogenic activity	Potential methane production	Measured methane production
UASB	I	42.8	15.2	0.320	4.86	-
UASB	IV	29.2	10.7	0.108	1.16	0.26
UASB	V	18.9	7.7	0.058	0.45	0.26
UASB	VIII	16.6	9.1	0.029	0.26	0.71
UASB-CMSD	XII	29.3	15.9	0.019	0.30	1.02
UASB-CMSD	XIV	21.9	13.6	0.016	0.22	0.75

Units: SS and VSS in $g \cdot \ell^{-1}$; Methanogenic Activity in g CH_4-COD$\cdot g^{-1}$ VSS$\cdot d^{-1}$;
Methane Production in g CH_4-COD$\cdot \ell^{-1} \cdot d^{-1}$

The %M reached 35% under these conditions. Furthermore, the system showed good stability and a high effluent quality: the mean values for effluent COD and SS were 136 and 31 $mg \cdot \ell^{-1}$, respectively, during Periods XIII and XIV.

Discussion

The efficiency of single UASB digesters treating domestic waste waters is in the range of 50 to 75% for COD removals and 70 to 80% for SS removals at typical HRT of 4 to 8 h (Lettinga et al., 1993; Kato, 1994; Wang, 1994) although the efficiency is more dependent on the characteristics of the waste waters treated and on design and operation parameters than on the HRT. An 85% threshold for COD removal by one-step anaerobic treatment has been established from extended batch assays (Van der Last and Lettinga, 1992).

Our results agree with previously published results, but the efficiency for both COD and SS removals is clearly a function of the HRT, for HRT<10 h. At the minimum HRT of 5 h, the COD removal was 53% and the SS removal was 63%. These values increased up to 73% and 80%, respectively, at an HRT of about 8 h for the UASB digester. However, the efficiency threshold

obtained at an HRT above 1 d is greater than 85% COD removal. This was probably due to the relatively high influent COD and to the non-septic characteristics of the domestic waste water used in this study. Furthermore, the removal efficiencies increased by about 5% when the UASB digester was combined with the CMSD system. This efficiency improvement was attributed mainly to the better mixing and waste water-biomass contact caused by the recirculation through the CMSD, that led to the increase of SS concentration in the UASB.

Results showed that the COD and SS reduction objectives of the Directive 91/271/CE could be reached only at HRTs greater than 24 h when a single-step UASB system was used. However, these objectives could be met by using the optimised UASB-CMSD system, provided that the UASB was operated at an HRT greater than 6 h and that an additional settling step was applied. Futhermore, some additional treatment may be necessary to meet BOD requirements, although this was not assessed in this work.

Other operational parameters like sulphates, orthophosphates, ammonium and total nitrogen were analysed in the UASB influent and effluent. Although the highest sulphate removal percentage reached was 44%, average values indicated that no significant sulphate removal took place in the UASB digester. However, no consistent mass balance for sulphate could be established, as the effluent concentration was higher than the influent one on occasions. On the other hand, effluent concentrations for orthophosphate and ammonium were always higher than the influent ones, indicating that at least part of the organic matter containing phosphorus or nitrogen was hydrolysed. A balance of influent and effluent ammonium and TKN indicated that about 62 to 74% of the proteins were hydrolysed.

Few studies have reported data about the characteristics of the biomass developed in UASB reactors treating this kind of waste water. Lettinga et al. (1993) indicated that a concentration of 30 to 40 g SS·ℓ^{-1}·digester, with a methanogenic activity of 0.1 g CH_4-COD·g^{-1} VSS·d^{-1}, may be obtained, even when the digester is started up without sludge seeding. However, there are no data that indicate whether this methanogenic activity corresponds to an average or to a point sample. In our study, similar methanogenic activities were found for the sludge samples from the first and second ports, at the bottom of the digester.

Data from Tables 2 and 3 may be used to calculate the average biomass concentration and the average methanogenic activity of the sludge. Results are shown in Table 4, together with the calculated methane production potential of the digester and the measured rCH_4. Both the average sludge concentration and the average methanogenic activity were lower than those predicted by Lettinga et al. (1993).

The total active biomass content decreased progressively, in spite of the high organic load converted into methane. The methane production potential of the UASB was determined from the VSS content and the specific methanogenic (using VFA as substrate) activity. This value decreased progressively after the start-up, stabilising in the range 0.22 to 0.30 g CH_4-COD·ℓ^{-1}·d^{-1} at the end of the second operation step, at a value lower than the amount of COD converted into methane. Therefore, the low amount of active biomass contained in the UASB digester could be one restrictive factor that needs to be resolved to enhance the reactor efficiency when operated at low HRT.

Furthermore, an additional substrate conversion pathway into methane, other than via VFA should be considered in order to explain the difference observed between the measured methane production rate (in the range of 0.7 to 1.0 g CH_4-COD·ℓ^{-1}·d^{-1}) and the methane production potential (0.22 to 0.30 g CH_4-COD·ℓ^{-1}·d^{-1}) predicted from the sludge concentration and methanogenic activity data.

The decreasing methanogenic activity of the UASB sludge, together with the behaviour of the methane production from the CMSD system (data not shown), suggest that methanogenic toxicity may be an important factor regulating the biomass quality in the UASB system. The methanogenic toxicity of domestic waste waters in a UASB digester has not been reported previously. However, the adsorption onto primary and secondary biological sludges of toxic substances that enter the treatment system with domestic and municipal waste waters has been monitored (Koopman and Bitton, 1986). These toxicants are mainly heavy metals and chlorinated and phenolic hydrocarbons. Several kinds of detergents are also present in domestic waste waters, that show microbial toxicity and poor biodegradability under anaerobic conditions. Also, long-chain fatty acids, like palmitic, stearic and oleic acids and others that are found in relatively high concentrations in domestic waste waters (Rinzema, 1988) may also cause methanogenic toxicity. Further research is required in order to assess the role of methanogenic toxicity during the treatment of domestic waste waters in anaerobic systems.

Acknowledgements

This work was supported by projects XUGA 10302A92, from the Galician Government (Spain), and AMB93-1212, from the CICYT.

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