The effect of operational conditions on the performance of UASB reactors for domestic wastewater treatment

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Abstract In this investigation, the performance of Upflow Anaerobic Sludge Blanket (UASB) reactors treating municipal wastewater was evaluated on the basis of: (i) COD removal efficiency, (ii) effluent variability, and (iii) pH stability. The experiments were performed using 8 pilot-scale UASB reactors (120 L) from which some of them were operated with different influent COD (COD_{Inf} ranging from 92 to 816 mg/L) and some at different hydraulic retention time (HRT ranging from 1 to 6 h). The results show that decreasing the COD_{Inf}, or lowering the HRT, leads to decreased efficiencies and increased effluent variability. During this experiment, the reactors could treat efficiently sewage with concentration as low as 200 mg COD/L. They could also be operated satisfactorily at an HRT as low as 2 hours, without problems of operational stability. The maximum COD removal efficiency can be achieved at COD_{Inf} exceeding 300 mg/L and HRT of 6 h.

Keywords COD removal efficiency; operational conditions; pH stability; sewage; UASB; variability

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Introduction

Although the advantages of using anaerobic systems for pre-treatment of sewage are recognised, concerns still exist about reactor stability and effluent variability. With respect to reactor operational stability, there are currently a large number of papers reporting results of anaerobic treatment of municipal wastewater. However, each paper refers to a strict range of operational conditions, making it difficult to compare the different investigations. Moreover, only limited data are available for upflow anaerobic sludge blanket (UASB) reactors treating sewage under extreme conditions, e.g. very short hydraulic retention times (HRT) or low influent COD concentrations (COD_{Inf}). Most of the reported results refer to anaerobic systems operated with HRTs within a range of 4–10 h for operational temperatures higher than 20 °C, and 6–14 h for temperatures lower than 20 °C (Seghezzo *et al.*, 1998; Kalogo and Verstraete, 1999). Thus, the operational limit of UASB reactors for the treatment of municipal wastewater is still not clear. With regards to effluent variability, very few studies directly deal with this subject, and the effect of operational procedures on the fluctuation of the effluent concentration was so far not reported.

In this work, experimental data were collected in order to evaluate the influence of the COD_{Inf} and the HRT on the performance of UASB reactors treating sewage. The performance is evaluated on the basis of: (i) COD removal efficiency, (ii) effluent variability, and (iii) pH stability during "steady state" conditions.

Materials and methods

The experimental investigation was carried out utilising 8 pilot-scale UASB reactors fed with pre-screened domestic sewage. The wastewater was withdrawn from the interceptor sewer of Campina Grande city, Brazil (350,000 inhabitants). Some of the reactors were operated with pre-screened sewage diluted with tap water using specific ratios of water to sewage, making it possible to achieve the required influent concentrations. The reactors operated in this work were denominated by R^{HRT}_{COD}, where the superscript index stands for the hydraulic retention time, and the subscript index stands for the total influent COD, both being the average during the "steady state" conditions. They were divided into two sets. Set 1, five reactors were fed at a constant flow of 20 L/h (HRT = 6 h) and with different COD_{Inf} (from 92 to 816 mg/L). Set 2, four reactors were operated with approximately the same COD_{Inf} ($\sim$800 mg/L), but with different HRTs (from 1 to 6 h). The operational parameters are presented in Table 1.

The reactors were built using PVC tubes with a volume of 120 L, a height of 4.0 m and internal diameter of 0.20 m. They were inoculated with anaerobic sludge discharged from a 5 m^3-UASB reactor, which had been operated for more than five years with raw sewage, with an HRT of 6 h. During the operation there was no intentional sludge discharge, and sludge production was evaluated from the sludge mass carried by the effluent. The liquid temperature was 27 °C ± 1.

At the end of the operational period, the maximum sludge accumulation inside each reactor was determined from the sludge concentration profile which was calculated using sludge samples withdrawn from the 14 taps installed along the reactors height. The sludge

Table 1 Performance of the different UASB reactors

	Set 1					Set 2			
Reactors	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^6_{92}	R^6_{816}	R^4_{770}	R^2_{787}	R^1_{716}
HRT	6	6	6	6	6	6	4	2	1
COD^{Tot}_{Inf}	816	555	298	195	92	816	770	787	716
COD^{SS}_{Inf}	566	420	216	120	55	566	450	512	486
COD^{Dis}_{Inf}	250	135	82	75	37	250	312	275	230
OLR	3.3	2.2	1.2	0.8	0.4	3.3	4.6	9.4	17.6
COD^{Tot}_{Eff}	343	213	104	89	43	343	416	436	469
COD^{Set}_{Eff}	177	117	70	53	30	177	214	237	271
COD^{SS}_{Eff}	38	39	20	4	2	38	137	147	168
COD^{X}_{Eff}	166	96	34	36	13	166	202	199	197
COD^{Dis}_{Eff}	139	77	50	50	28	139	78	92	103
COD_{CH4}	472	347	201	107	48	472	351	312	n.d.
E_{Tot}	57.0	60.1	64.0	53.3	50.4	57.0	45.5	44.1	36.6
E_{Set}	76.6	76.7	74.4	69.3	66.0	76.6	72.0	69.6	63.1
E_{SS}	93.3	90.7	90.8	97.1	96.4	93.3	70.2	71.3	65.4
E_{Dis}	44.6	42.5	39.7	33.7	25.0	44.6	75.1	67.2	55.2
Alk_{Eff}	393	286	197	159	157	393	383	393	368
VFA_{Eff}	49	25	27	12	21	49	43	40	111
M_X	2.104	1.950	1.366	1.162	2.377	2.104	2.291	2.332	1.933
SRT	49	74	145	115	558	49	26	13	6
Time	226	209	209	209	83	226	154	154	83

HRT is the hydraulic retention time (h). COD is the chemical oxygen demand (mg COD/L) and the indexes stand for: Inf = influent, Eff = effluent, Tot = total, Set = settled, SS = suspended solids, Dis = dissolved, X = excess sludge, CH4 = methane production. OLR is the organic loading rate (kg COD/m^3 day). Alk_{Eff} is the effluent total alkalinity (mg $CaCO_3$/L); VFA_{Eff} is the effluent total volatile fatty acids (mg/L); M_X is the mass of volatile solids in the reactors (kg VS); SRT is the sludge retention time (days); Time is the total time of operation (days). $E_{Tot}(\%) = (1 - COD^{Tot}_{Eff}/COD^{Tot}_{Inf}) \times 100$; $E_{Set}(\%) = (1 - COD^{Set}_{Eff}/COD^{Tot}_{Inf}) \times 100$; $E^{Set}_{SS}(\%) = (1 - (COD^{Set}_{Eff} - COD^{Dis}_{Eff})/COD^{SS}_{Inf}) \times 100$; $E_{Dis}(\%) = (1 - COD^{Dis}_{Eff}/COD^{Dis}_{Inf}) \times 100$. Reactor R^6_{816} is repeated to create the two sets above.

retention time (SRT) was calculated according to Cavalcanti *et al.* (1999), as the ratio between the volatile sludge mass in the reactor and the daily sludge production calculated from the amount of settleable volatile suspended solids (VSS) in the effluent. The performance and stability of the reactors were evaluated based on COD removal efficiency, SS removal efficiency, gas production, specific methanogenic activity (SMA), maximum sludge accumulation, in addition to both influent and effluent solids, VFA, pH and alkalinity. The COD removal efficiency was expressed in two ways: (i) total effluent/total influent ratio, and (ii) settled effluent/total influent ratio, after 1 hour of settling time. The first ratio represents the overall removal efficiency, and the second indicates the treatment potential that could be attained if efficient settling would be applied and excess sludge was discharged from the UASB reactor (Cavalcanti *et al.*, 1999).

All physical-chemical analyses were performed as recommended by APHA (1995). Raw samples were used for Total COD; filtered samples were performed through 4.4 mm folded paper filters (Schleicher & Schuell $595\frac{1}{2}$, Germany) for paper filtered COD; and through 0.45 mm membrane filters (Schleicher & Schuell ME 25, Germany) for dissolved COD. The micro-COD method was used for all COD analysis. Total VFA followed the procedure described in Buchauer (1998). Specific methanogenic activity (SMA) was determined according to Chaggu (2004).

Results and discussion

The effect of influent concentration on reactor performance

COD removal efficiency. Table 1 shows that with COD_{Inf} lower than 300 mg COD/L, the efficiency of the UASB reactors decreases. However, with values exceeding 300 mg COD/L, the reactors achieved their maximum efficiency, viz. around 57–60% for total-effluent COD and around 77% for settled-effluent COD. The analysis of variance showed that there were no significant differences ($\alpha = 0.05$) among reactors R^6_{816}, R^6_{555}, and R^6_{298} for COD removal efficiencies.

It was expected that low substrate concentrations would result in a decreased reactor performance due to the mass transfer limitation at lower dissolved COD concentration. Even so, the UASB reactors were apparently able to treat sewage with an average COD_{Inf} as low as 92 mg/L, with efficiencies around 66% (based on settled effluent). Assuming that the effluent SS is the non-settleable suspended COD fraction in the effluent, a slight decrease in the SS removal efficiency (E_{SS}) occurred at increased influent COD. The results of E_{SS} are opposite to what was expected. According to Mahmoud *et al.* (2003), the entrapment capacity increases at high influent SS concentrations because of the enhanced collision opportunity of the influent solids and the sludge bed. Nonetheless, the high E_{SS} removal obtained under all imposed conditions, especially in reactor R^6_{195}, was the main cause of such high total COD removal efficiency at very low influent concentration. According to Kato (1994), the capacity of UASB reactors for treating very low strength wastewaters can be explained by means of the half saturation value, ks, of the Monod model. All reactors operated with HRT of 6 h contained flocculent sludge, which has a low apparent k_s and thus high affinity and capacity to treat sewage with a low substrate concentration.

The SMA slightly increased with decreasing influent concentrations, viz. from 0.18 kg COD/kg VS day at 30 °C for the reactor operated with COD_{Inf} of 816 mg/L (reactor R^6_{816}) to 0.23 and 0.22 kg COD/kg VS day for reactors operated with COD_{Inf} of 195 and 92 mg COD/L respectively (reactors R^6_{195} and R^6_{92}). However, total and settled COD removal efficiencies and methanisation (results not shown) decreased with diminishing COD_{Inf}. Moreover, at lowered COD_{Inf} the reactors resulted in decreased dissolved COD removal efficiency (E_{Dis}) and decreased $VFA_{Eff}/COD^{Dis}_{Eff}$ ratio. This may indicate that at low concentrations (down to 200 mg COD/L), the acidification was the limiting step, which is in agreement with the observations of Kato (1994).

Effluent and efficiency variability. The coefficient of variation (CV), which is the standard deviation expressed as a percentage of the mean, was used to evaluate effluent and removal efficiency variability. In this work, only the settled effluent was considered, as the total effluent COD includes the excess sludge. Figure 1A shows the calculated values of CV of the effluent COD and of treatment efficiency. The effluent COD and removal efficiency fluctuation tend to increase at a lower COD_{Inf}. The influent COD fluctuation seems to be the main cause of the effluent variation because the effluent fluctuation increased as the influent fluctuation increased. However, this cannot be the only reason as reactors which were operated at lower influent concentration gave an effluent with higher fluctuations than the influent (see points above the 45-degrees line in Figure 1B). It is possible that at a low COD concentration, the variation increased due to a higher analytical error. However, it is also possible that the variability of the biological process caused an additional fluctuation, as reported by Weber and Juanico (1990).

pH stability. The operational stability of the UASB reactors was evaluated in terms of bicarbonate alkalinity, pH, total VFA concentration, VFA/bicarbonate alkalinity ratio and buffer capacity (results of bicarbonate alkalinity and buffer capacity are not shown). According to Behling *et al.* (1997), a value greater than 0.4 for the VFA/bicarbonate alkalinity ratio might indicate that the anaerobic digester becomes unstable. The buffer capacity was assessed based on the methodology presented by van Haandel (1994). The VFA concentration in the effluent of all reactors of Set 1 was low (less than 1 mmol/L), and the bicarbonate alkalinity and buffer capacity was relatively high. Accordingly, the VFA/bicarbonate alkalinity ratio was always less than 0.3. The pH remained in the range 6.9–7.7 throughout the duration of the experimental period, so that there was no danger of reactor instability.

The effect of the hydraulic retention time on reactor performance

COD removal efficiency. Table 1 shows that with an HRT between 1 and 6 h (upflow velocity – V_{up} within the range 0.64–3.8 m/h) the efficiencies increased with longer HRT (or lower V_{up}). This is similar to the results found by van Haandel and Lettinga (1994), i.e. a decrease when V_{up} increases. The data indicates that there is a trend for COD removal efficiency based on settled effluent to become constant for HRT longer than 4 hours (around 77%). This is because the SS removal efficiency was higher than 90%. Moreover, methanisation of the removed COD was 74% for the reactor operated with an HRT of 6 h (results not shown). This means that COD removal efficiency

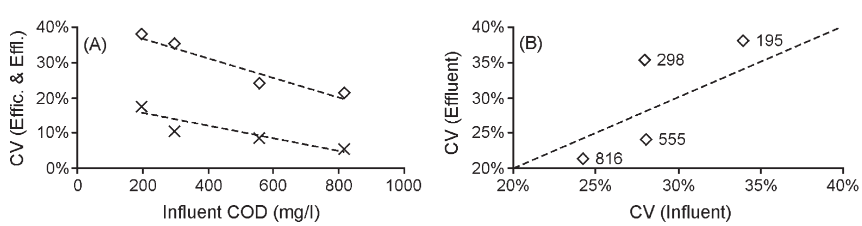

Figure 1 (A) Effect of the COD_{Inf} on the fluctuation of effluent COD (◇) and treatment efficiency based on settled effluent COD (X). (B) Effect of the influent variability on the effluent variability. Values inside graph B represent COD_{Inf}

and methanisation can hardly be improved by an increase in HRT, as they are already very close to the maximum value (the biodegradability of the influent was around 77%).

Reactors R^4_{770}, R^2_{787} and R^1_{716} showed similar excess sludge washout, viz. around 200 mg COD/L, while for reactor R^6_{816} (operated with OLR = 3.3 kg COD/m^3 day) this value amounted to 166 mg COD/L. The total effluent SS concentration (as COD) increased considerably at HRT lower than 6 h (Table 1), and accordingly the SS removal efficiency decreased. This is an indication that at lower HRT the hydrolysis step could not proceed properly. The analysis of variance showed that there is no difference ($\alpha = 0.05$) between the results of SS removal efficiency of the reactors operated with HRT of 2 and 4 hours.

Effluent and efficiency variability. The influence of hydraulic retention time on the fluctuation of the reactor performance is depicted in Figure 2A. Reactor R^6_{816} (HRT = 6 h) had the highest influent fluctuation (CV = 24.2%), but its COD removal efficiency did not vary significantly. In contrast, reactor R^1_{716}, operated with an HRT of 1 hour and with an influent CV of only 18.2%, resulted in an effluent with the highest fluctuation. The probable explanation is the higher equalisation capacity of the reactor at a longer HRT, which can smooth the influent fluctuation. As illustrated in Figure 2B, the influent variation has a strong effect on the effluent fluctuation.

pH stability. The VFA concentration in the effluent of reactors R^6_{816}, R^4_{770}, and R^2_{787} was low (less than 1 mmol/L), and the pH during the whole experimental period remained in the range 7.0–8.2. Buffer capacity was favourable in all reactors, and the VFA/alkalinity ratio was lower than 0.3. Reactor R^1_{716} was operated under extreme conditions, with an HRT of 1 h. However, despite the fact that pH values were still in their optimum range for the anaerobic process, (varying from 6.6 to 7.1), effluent VFA concentration was high (average of 111 mg/L) and the VFA/bicarbonate alkalinity ratio appeared to be at a risky level (0.5). In contrast, buffer capacity was very high due to the high influent alkalinity.

Final discussion

In tropical countries, where sewage temperatures are $> 20\,^\circ$C, UASB reactors can achieve the maximum COD removal efficiency (around 57–60% for total effluent and 77% for settled effluent) at COD_{Inf} exceeding 300 mg COD/L and HRT of 6 h. The reactors operated with HRT of 6 h and COD_{Inf} of 816 mg/L resulted in SS removal efficiency (E^{Set}_{SS}) of 93.3% and methanisation of the removed COD of 73.8%. This means that the efficiency can hardly be improved, so that it seems useless to operate UASB reactors in tropical countries with HRT exceeding 6 h.

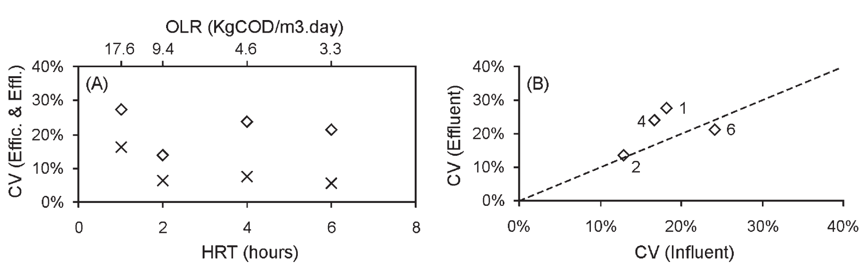

Figure 2 (A) Effect of the HRT on the fluctuation of effluent COD (◇) and treatment efficiency based on settled effluent COD (X). (B) Effect of the influent variability on the effluent variability. Values inside graph B represent HRT

The results obtained from reactors operated with short HRT can be used for an evaluation of a two-step process for sewage treatment, such as the HUSB (hydrolysis upflow sludge bed reactor) + UASB, supported by Wang (1994). This system was meant to treat sewage at temperatures below 20 °C, as under this condition the hydrolysis proceeds slowly and SS accumulate, decreasing the SRT and preventing the development of the methanogens in the first step. However, at temperatures of around 27 °C, methanogenesis was not limited at HRT as low as 2 h and V_{up} of 1.9 m/h (SRT of 13 days). This is an indication that the application of a two-step system, as proposed by Wang (1994), is not suitable for tropical countries with sewage concentration in the range of 300–800 mg COD/L, as methanogenesis will always occur in the first step. In the present study, we simulated a two-step system UASB-secondary settler by determining the settled effluent. It is in fact the opposite of which was proposed by Wang (1994), as the SS removal occurs in the second step. For the operational mode imposed during our research, i.e. reactor operated without intentional sludge discharge, this fictitious secondary settler was fundamental for the improvement of effluent quality increasing the treatment efficiency.

The results of this investigation show that for a particular HRT, the UASB reactors maintain approximately the same COD removal efficiency irrespective of the COD_{Inf} (at least in the range of 300–800 mg COD/L). When a particular organic load from a municipality is to be treated, the COD concentration may increase when dilution with other waters (rain, infiltration) is avoided. When this happens, the flow rate decreases and the reactor can be designed with a smaller volume without deteriorating the performance.

Conclusions

COD removal efficiency. Decreasing the influent concentration and/or decreasing the HRT leads to decreased efficiencies. The maximum COD removal efficiency is achieved with an HRT longer than 4 hours, and influent concentration higher than 300 mg COD/L.

Effluent variability. Effluent variability is highly dependent on the influent variability. The fluctuations increase with decreased HRT due to a decreased reactor equalisation capacity. The effluent variability also increases with lowered influent concentrations because analytical errors become more noticeable.

pH stability. UASB reactors treating municipal wastewater in tropical countries are extremely stable with regards to pH and buffer capacity, indicating that it is very difficult for an operational or environmental situation to arise that causes souring. The studied UASB reactor only showed some evidences of pH instability at extreme operational conditions.

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