The effects of hydraulic and organic shock loads on the robustness of upflow anaerobic sludge blanket reactors treating sewage


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Abstract In this investigation, the robustness and stability of UASB reactors was evaluated on the basis of four indicators: (i) COD removal efficiency; (ii) effluent variability; (iii) pH stability; and (iv) recovery time. The experiments were carried out using six pilot-scale UASB reactors fed with domestic sewage and operated under different operational conditions. After establishment of a "steady-state", organic and hydraulic shock loads (six times the loading rate during six hours) were imposed. The results show that the UASB reactors are robust systems with regards to COD removal efficiency and pH stability when exposed to shock loads. However, this reactor cannot attenuate the imposed fluctuation in the influent COD. A secondary treatment unit is needed to retain the expelled sludge occurring as a result of a hydraulic shock load, or prior to the shock, a sufficient amount of sludge needs to be discharged from the reactor.

Keywords COD removal efficiency; effluent variability; pH stability; recovery time; shock load; upflow anaerobic sludge blanket reactor

Introduction

Although anaerobic wastewater treatment (AnWT) systems have already been applied successfully under different operational (organic and hydraulic loading rate) and environmental conditions (van Haandel and Lettinga, 1994; Leitão, 2004), a number of critical questions still remain. One of the bottlenecks is the lack of knowledge about the capacity of high rate anaerobic systems, such as anaerobic upflow sludge blanket (UASB) reactors, to cope with severe environmental and operational variations. This may cause serious problems of reliability and has led to a certain prejudice against the use of these systems for the treatment of municipal sewage. In the case of sewage, the cyclical nature of human activities leads to a variable production over the day (Campos and von Sperling, 1996). Moreover, inappropriate connections of runoff water and rainfall, variation of the population in tourist areas, as well as operational procedures at the sewerage and treatment plant, can result in increasing hydraulic and organic loads (Orhon et al., 1999).

The typical response of AnWT plants to variable flow or concentration conditions may be incomplete methanogenesis, resulting in accumulation of volatile fatty acids (VFA) (mainly propionate and butyrate), decrease in pH and bicarbonate alkalinity, lower biogas production and change in biogas composition, i.e. an increase of the CO₂ and H₂ gas content, and sometimes in a temporary higher sludge washout (Cohen et al., 1982; Eng et al., 1986; Leitão et al., 2006). Consequently, strong variations in flow and concentration may detrimentally affect the average efficiency of UASB reactors. The magnitude
of these undesirable effects depends on the characteristics of the treatment system (reactor configuration, ratio of organic load to organic load potential, and availability of a fault detection and control system), and also on factors related to the variation itself, such as the type of the imposed shock loads, their extent, frequency and duration (Xing et al., 1997; El Farhan and Shieh, 1999; Leitão et al., 2006).

The present study evaluated the effects of drastic variations in the influent concentration (COD$_{inf}$) and hydraulic retention time (HRT) on the performance of UASB reactors treating domestic sewage.

**Materials and methods**

The experimental investigation was carried out, using six pilot-scale UASB reactors described by Leitão (2004) (height of 4.0 m, internal diameter of 0.2 m, and working volume of 120 L), which were fed with pre-screened domestic sewage of the city of Campina Grande (350,000 inhabitants), at a temperature of around 27°C. They had a modified gas–solid–liquid separator, and were equipped with dosing pumps, gas samplers, and 14 sludge collection points.

The main operational parameters used during the “steady-state” condition are presented in Table 1. The reactors 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 are the average during the “steady-state” conditions.

The pilot-scale reactors 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, and with a HRT of 6 h. The pilot-scale reactors were filled to the top with this sludge, and then operation was started at a constant flow and having a particular influent COD (COD$_{inf}$). The excess sludge was washed out during the first few days of the experimental period. During the entire period of operation there was no intentional sludge discharge, and sludge production was evaluated from the sludge mass carried by the effluent.

The six pilot-scale UASB reactors were organised into two sets. In Set 1, four reactors were fed at a constant flow of 20 L/h (HRT = 6 h) and with different COD$_{inf}$. In Set 2, three reactors were operated with approximately the same COD$_{inf}$ (~800 mg/L), but with different HRTs. The data of one of the reactors was used to create the two sets.

After establishment of a “steady-state” condition, organic and hydraulic shock loads were imposed. Organic shock loads were carried out by increasing the influent concentration approximately five times during a period of 6 h, while maintaining a constant HRT. One month after the organic shocks were imposed, the hydraulic shock loads were performed by increasing the flow rate three times, also for a period of 6 h, while maintaining an almost constant COD$_{inf}$. These procedures imply that the organic loading rates (OLRs) were also increased five and three times during the organic and hydraulic shock loads respectively.

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Set 1</th>
<th>Set 2</th>
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<tbody>
<tr>
<td>R$^{6}$</td>
<td>R$^{6}$</td>
<td>R$^{6}$</td>
</tr>
<tr>
<td>HRT (h)</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$V_{up}$ (m/h)</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td>COD$_{inf}$ (mg/L)</td>
<td>816</td>
<td>555</td>
</tr>
<tr>
<td>OLR (kgCOD/m$^3$.day)</td>
<td>3.3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Reactor R$^{6}$ is repeated to create the two sets above.
For the organic shock loads, the feed concentration was enhanced by a mixture of vinasses and primary sludge, according to the scheme in Table 2. The hydraulic shocks were imposed without altering the sewage characteristics.

The robustness of the UASB reactors under shock load conditions was evaluated on the basis of four indicators: (i) the capacity of the reactors to absorb the imposed shock load (COD removal efficiencies), which were calculated based on the mass of the COD imposed to the system during the period of 24 h (starting from the beginning of the shock), and on the mass of COD in the effluent during the same period; (ii) the extent in which the quality of the effluent is affected by a shock load (effluent variability), which is the maximum value for the ratio between the 6 h moving average and the “steady-state” average of the settled effluent COD; (iii) the pH and bicarbonate stability during shock loads (pH stability), which was evaluated based on the ratio VFA/ bicarbonate alkalinity; and (iv) the time necessary for the reactor to recover from the shock loads (recovery time), which is the time required (starting from the beginning of the shock) for the settled effluent COD values to return to the average values found under “steady-state” conditions.

All physical-chemical analyses were performed as recommended by the Standard Methods (1995). The micro-COD method was used for all COD analysis. In this work, settled effluent COD is the concentration of the supernatant after 1 h of settling time.

Results and discussion
Organic shock loads
The results of the organic shocks loads are depicted in Figure 1. To limit the number of graphs, Figure 1 only shows the results of the reactors operated with the highest and the lowest COD_{inf} (R6816 and Reactor R4787), and the results of reactors operated at the longest and the shortest HRT, respectively R6816 and R2298. The trends observed in the other reactors (R555, R5298 and R770) were similar.

After the organic shock load started, the reactor performance temporarily deteriorated, which was mainly due to increased settled effluent COD and higher sludge washout. The deterioration of the settled effluent COD can be attributed to a higher effluent VFA concentration, clearly demonstrating that the reactors were overloaded with respect to methanogenesis.

The increased SS concentration in the effluent coincided with an elevated gas production, which might be the main reason for this phenomenon. It should be taken into account that a higher influent SS concentration was applied during the shock loads as a result of the addition of primary sludge consisting of relatively well settleable matter. As a result, part of the non-entrapped SS may have ended up as excess sludge instead of effluent SS (non-settleable fraction). The sludge washout was mainly due to the

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Set 1</th>
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<tbody>
<tr>
<td>R6816</td>
<td>R655</td>
<td>R655</td>
</tr>
<tr>
<td>Total COD</td>
<td>4112 (5.0)</td>
<td>2969 (5.3)</td>
</tr>
<tr>
<td>Suspended COD</td>
<td>1011 (1.8)</td>
<td>798 (1.8)</td>
</tr>
<tr>
<td>Dissolved COD</td>
<td>3101 (12.4)</td>
<td>2211 (16.5)</td>
</tr>
<tr>
<td>Total VFA</td>
<td>462 (2.8)</td>
<td>1069 (12.1)</td>
</tr>
</tbody>
</table>

All values are in mg/L. Reactor R6816 is repeated to create the two sets above.
expansion of the sludge bed during increased hydraulic loading rate and higher gas production during the increased OLR.

In general, when organic shock load was imposed, the reactors operated with lower influent concentrations and shorter HRTs resulted in higher COD removal efficiencies (based on the 24 h average of settled effluent), as shown in Table 3. This can be attributed to the higher “reserve” capacity of these reactors to cope with organic shock loads. However, the relatively high sludge washout of reactors operated at HRTs of 4 and 2 h caused a deterioration of the total effluent COD.

The settled effluent COD concentration (based on a 6 h average) increased four- to eight-fold, compared to the “steady-state” values, for all reactors operated under a shock load of five times the influent concentration. This is an indication that the UASB reactors cannot attenuate strong fluctuations in the influent concentration (see effluent variability in Table 3).

The recovery time of an organic shock load (Table 3) is highly dependent on HRT. Reactors operated at an HRT of 6 h needed 14–18 h after the cessation of the shock to return to the “steady-state” conditions, whilst reactors operated at a shorter HRT needed 4–6 h.

There was a trend for the reactor contents to acidify in almost all cases when the five-fold organic shock loads were imposed (Table 3). This was reflected in the increasing

**Figure 1** Effect of organic shock load on the performance of UASB reactors. Dashed lines represent the duration of the shock loads

**Table 3** Performance of the different UASB reactors under organic and hydraulic shock loads

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Set 1</th>
<th>Set 2</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$R_{16}^1$</td>
<td>$R_{16}^2$</td>
</tr>
<tr>
<td>Organic shock loads</td>
<td>Total efficiency</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Settled efficiency</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Effluent variability</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>Recovery time (h)</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>VFA/bicarbonate alkalinity (max)</td>
<td>2.1</td>
</tr>
<tr>
<td>Hydraulic shock loads</td>
<td>Total efficiency</td>
<td>-28%</td>
</tr>
<tr>
<td></td>
<td>Settled efficiency</td>
<td>72%</td>
</tr>
<tr>
<td></td>
<td>Effluent variability</td>
<td>147%</td>
</tr>
<tr>
<td></td>
<td>Recovery time (h)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>VFA/bicarbonate alkalinity (max)</td>
<td>0.8</td>
</tr>
</tbody>
</table>
effluent VFA concentration and in the ratio VFA/bicarbonate alkalinity that was far beyond the risky level. 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.

**Hydraulic shock loads**

The results of the hydraulic shock loads are depicted in Figure 2, similarly to the description for the organic shock load experiments in Figure 1. Results are only shown for reactors operated with the highest and the lowest COD_{inf}, and with the longest and the shortest HRT. The performance of all other reactors followed the same trend in performance as shown in these figures.

After the hydraulic shock load started, the total effluent COD immediately increased, reaching a peak within the first two or three hours. This peak was mainly caused by sludge washout as a consequence of the high upflow velocity and gas production on the dynamics of the sludge bed, as explained by Leitão (2004). The imposed hydraulic load fluctuations expand or shrink the sludge bed due to a new equilibrium among the upflow velocity, gas production and sludge settling velocity. Depending on the hydraulic load variation, a higher or lower settleable volatile solids concentration in the effluent is expected as a result of the washout of lighter biomass, the decreased filtration capacity of the sludge bed at higher upflow velocities, and the disintegration of granules or flocks under the abrasive action of shear forces. Expansibility of the sludge bed in UASB reactors is highly dependent on way the system was operated under preceding “steady-state” conditions, e.g. the sludge bed was found to be more expansible when the reactors were operated at a higher HRT and/or lower COD_{inf} Leitão (2004). The amount of sludge washed out from the system during the three-fold hydraulic shock load reached up to 15% and 30% of the sludge mass inside of the reactors operated with HRT of 6 and 2 h respectively. It is worthwhile to note that, during “steady-state” conditions, the reactors were operated without sludge discharge. However, these expulsions of sludge did not deteriorate the long-term performance of the reactors.

In cases when the reactors were operated with low influent concentrations, the oxygen content in the influent during the hydraulic shock may have caused a certain inhibition of the methanogenesis, as the VFA concentration increased until the shock ceased (Kato et al., 1997). The dissolved oxygen concentration in the influent was approximately 4 mg/L during hydraulic shock loads in reactor operated with influent COD concentration of 195 mg/L.

![Figure 2](https://iwaponline.com/wst/article-pdf/54/2/49/478301/49.pdf)

*Figure 2* Effect of hydraulic shock load on the performance of UASB reactors. Dashed lines represent the duration of the shock loads.
The reactors operated at lower influent concentration showed lower COD removal efficiency (Table 3) when a hydraulic shock load is imposed. In these cases, the decreased capacity to entrap the suspended solids (either the non-settleable or the excess sludge) was the main cause for the deterioration of the short-term performance of the reactors.

The settled effluent COD varied in the range of 120–240% for all reactors operated under a shock load of three times the flow rate (Table 3). However, the total effluent COD varied up to 2300% during the transient conditions due to the heavy sludge washout. In fact, sludge washout during hydraulic shock loads was the main reason for the negative values of the total efficiency. A secondary unit seems essential to mitigate such effects.

The recovery time of a hydraulic shock load was always very short. The values for settled effluent COD achieved those of the “steady-state” conditions within at maximum 3 h after the shock load ceased (Table 3).

In most cases, the pH remained almost unaffected by the three-fold hydraulic shock loads (Table 3). However, the effect of a long-term hydraulic shock on reactors operated with low influent concentration is unclear, since the high oxygen load imposed to the systems may have a detrimental effect on methanogenesis, but not on acidogenesis.

Conclusions
We concluded that: UASB reactors are robust with regard to their ability to (partially) absorb the short-term (6 h) organic and hydraulic shock loads. UASB reactors treating sewage are also robust with regard to pH stability when exposed to three-fold hydraulic shock loads. Organic shock loads up to 5 times during 6 h caused little pH change, but a gradual increase of VFA was observed. This might have caused a decrease of pH if the shock load persisted for a longer period. UASB reactors have no capacity to attenuate strong fluctuation in the influent COD. Finally, a secondary treatment unit is always necessary to retain the expelled sludge due to a hydraulic shock load when the UASB reactor is operated without intentional sludge discharge.

Acknowledgements
This work was accomplished with the support of CNPq (Project no. 200198/00-9), a Brazilian government institute responsible for the development of science and technology.

References


