Load limit of a UASB fed septic tank-treated domestic wastewater

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ABSTRACT

Performance of a 250 L pilot-scale up-flow anaerobic sludge blanket (UASB) reactor, operated at ambient temperatures, fed septic tank effluents intermittently, was monitored for hydraulic retention time (HRT) from 18 h to 4 h. The total suspended solids (TSS), total chemical oxygen demand (CODT), dissolved chemical oxygen demand (CODdis) and suspended chemical oxygen demand (CODss) removal efficiencies ranged from 20 to 63%, 15 to 56%, 8 to 35% and 22 to 72%, respectively, for the HRT range tested. Above 60% TSS and 47% CODT removal were obtained in the combined septic tank and UASB process. The process established stable UASB treatment at HRT/C216 h, indicating a hydraulic load design limit. The tested septic tank–UASB combined system can be a low-cost and effective on-site sanitation solution.

INTRODUCTION

Decentralized Wastewater Treatment System (DEWATS) might be an attractive choice in developing countries that allows locals to deal with their situation when there is inadequate action taken by the central governing body (Green & Ho 2005). Moreover, it has been observed that out of five centralized aerobic wastewater treatment plants (WWTPs) in Nepal only one is in partial operation. On the contrary, all DEWATS are in full operation.

Anaerobic wastewater treatment as part of DEWATS can be a sustainable process for on-site (individual or cluster) treatment due to its low or no energy consumption, low space requirement and relatively simple reactor design (Zeeman & Lettinga 1999). Additional advantages of anaerobic wastewater treatment are production of methane and bio-fertilizer, improved sanitation and public health, and low sludge production compared with aerobic processes. These advantages are partly explained by the fact that aeration is eliminated.

Domestic wastewater has generally low concentration of chemical oxygen demand (COD) and relatively high concentration of particulate matter. An initial hydrolysis step to convert particulate matter into soluble substrate can therefore be required, which is significantly affected by temperature and retention time and is usually a rate-limiting step for low-temperature conditions (Lew et al. 2011). In tropical countries, the up-flow anaerobic sludge blanket (UASB) reactor for domestic wastewater has wide acceptance; however, its use in countries with lower temperatures is limited (Elmitwalli et al. 2001; Chong et al. 2012). A possible way to improve UASB performance is to supply pulse feeding and combine it with septic tank (ST) pre-treatment. Standard septic tanks are useful for removal of inert solids and preliminary hydrolysis of particulate organic matter, though optimized fermentation and hydrolysis depend on their design (Richard et al. 2005; Rocktäschel et al. 2013).

Mahmoud et al. (2005) reported that UASB up-flow velocity should be high enough to provide good contact between feed and biomass (microorganisms) to reduce chances of channel formation. This is usually achieved by a recycle pump line from the top of the reactor to the bottom to maintain a water up-flow velocity > 1 m/h (Tchobanoglous et al. 2003). Barber & Stuckey (1999) reported that up-flow velocity influences floculent and granular growth and thus anaerobic conversion of organic material present in the wastewater. Recycle pumping does, however, add complexity and cost, so pulse feeding was applied here as an alternative to obtain the needed mass transfer. Such pulsation stimulates the development of granular sludge with both improved settling and degradation properties (Franco et al. 2005; Rocktäschel et al. 2013). The pulse feeding strategy applied here was assumed to serve these purposes and was compatible with standard, robust and cheap pumps that can be used for intermittent feeding.

About 50% of urban toilets in Nepal are already connected to septic tanks, whereas rural toilets are connected
to either a settling tank or a cesspool (SACOSAN, 2013). In this context, a septic tank, serving as the primary treatment step, combined with a pulse-fed UASB reactor as secondary treatment is proposed as an appropriate on-site treatment model and investigated here. Pulse feeding the UASB was chosen because this mode of operation has been found simple and efficient (Lohani et al. 2013). The ST-UASB treatment process evaluated here is installed at Kathmandu University (KU) as a full-scale pilot research plant. The main purpose of the analysis presented here is to determine treatment performance as a function of reactor loading rates.

**MATERIAL AND METHODS**

The septic tank-UASB combined system at KU premises was operated with wastewater generated from a girls’ dormitory and staff quarters. The wastewater was collected in an already existing ST with a volume about 13.5 m$^3$ and hydraulic retention time (HRT) of 18 h. The ST provided removal of suspended solids and allowed hydrolysis of particulate organic matter to generate a feed solution that was appropriate for UASB. The UASB reactor tested was 250 L (1 m height and 0.56 m diameter; made up of PVC barrel). The schematic of the complete plant is shown in Figure 1.

**Pilot plant start-up and operation**

The ST-UASB combined system was started up in the month of December at 9.5 °C ambient temperature. The UASB reactor was inoculated with 40 L (20% of the liquid volume of the reactor) by anaerobic slurry (no granules) obtained from manure-fed biogas plant. The inoculum sludge characteristics in terms of total chemical oxygen demand (COD$_T$), total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS) and VS/TS were 16 g/L, 14 g/L, 9.8 g/L, 13 g/L, 8.4 g/L and 0.7, respectively. The UASB reactor was operated for 6.5 months, with HRT dropping from 10 to 1 d HRT in a preliminary test reported elsewhere (Lohani et al. 2013).

In this study the reactor was operated one and half months at 18 h HRT, one month at 12 h HRT, 1.5 months at 8 h HRT, two months at 6 h HRT, one month for 5 h HRT and one month for 4 h HRT. The changes in HRT were made once the COD removal efficiencies were nearly constant for about two weeks at each HRT level.

The ST effluent was pumped intermittently to the UASB reactor using an automatic timer. The reactor was fed 17 L (less than the volume of the S-L-G separator (Figure 1)) of sewage volume in each feed pulse with 12 pulses per HRT for all cases studied here. The length of feeding pulse in

![Figure 1 | Schematic diagram of septic tank-UASB combined system (p – pump used for UASB pulse feeding).](https://iwaponline.com/wst/article-pdf/72/8/1455/466642/wst072081455.pdf)
each pulse was about 3 minutes. Reactor loading was changed by increasing the pulse feeding frequency. The plant was running at ambient temperature in the range from 0 °C to 30 °C.

Analysis

Grab samples of wastewater were collected from sample ports 1, 2 and 3 (Figure 1) and were analysed for COD<sub>T</sub>, suspended chemical oxygen demand (COD<sub>s</sub>s), dissolved chemical oxygen demand (COD<sub>dis</sub>), TSS, pH, and temperature. All parameters were analysed in accordance with standard analytical methods (APHA 1995). Raw samples were used to measure COD<sub>T</sub>, whereas 0.45 μm membrane-filtered (Whatman GF/C, UK) samples were used for dissolved COD. A diaphragm type gas flow meter (GTEC, G1.6R, made in Korea) was used to measure the amount of biogas produced (diaphragm expands and contracts with the gas flow driving a counting device via a crank shaft). The statistical analysis was done using Microsoft Excel spreadsheet.

COD mass balance of UASB reactor

The overall COD mass balance is as given in Equation (1) (Al-Shayah & Mahmoud 2008).

\[
COD_{T,inf} = COD_{CH4} + COD_{T,eff} + COD_{accumulated}
\]  

(1)

Where

- COD<sub>T,inf</sub> and COD<sub>T,eff</sub> are UASB influent and effluent total COD (mgCOD/L);
- COD<sub>accumulated</sub> is amount of COD accumulated in the UASB reactor (mg COD/L);
- COD<sub>CH4</sub> is amount of produced CH<sub>4</sub> (mg CH<sub>4</sub> as COD/L).

The COD balance is used to calculate hydrolysis and methanogenesis as follows.

Hydrolysis and methanogenesis

Hydrolysis (H) and methanogenesis (M) percentages are estimated according to Equations (2) and (3) (Al-Shayah & Mahmoud 2008).

\[
(H\%) = 100 \left( \frac{COD_{CH4} + COD_{dis,eff} - COD_{dis,inf}}{COD_{T,inf} - COD_{dis,inf}} \right)
\]  

(2)

\[
(M\%) = 100 \left( \frac{COD_{CH4}}{COD_{T,inf}} \right)
\]  

(3)

RESULTS AND DISCUSSION

The results presented in Table 1 and Figures 2 and 3 show the parameter concentrations and removal efficiencies of the reactor at different organic loading rates (OLRs) and HRTs. The OLRs at 18, 12, 8, 6, 5 and 4 h HRT were on average 1, 1.7, 2.2, 3.3, 3, and 4.1 kgCOD/m<sup>3</sup>d, respectively. Note that OLR was not directly proportional to HRT, as inlet COD<sub>T</sub> was lowest during the 5 h and 4 h HRT testing periods, perhaps due to slightly increased summer season per capita water consumption. Moreover, the average influent temperatures for these different HRT operations were 17 °C, 9 °C, 13 °C, 19 °C, 22 °C and 22 °C, respectively, due to seasonal variations. Reasonably high removal of organic matter (more than 60% and 47% TSS and COD<sub>T</sub> removal, respectively) was achieved at all conditions tested for the combined ST-UASB process. These results are further discussed in the following.

UASB

The average TSS removal efficiency ranged from 20 to 63%, COD<sub>T</sub> removal efficiency from 15 to 56%, COD<sub>s</sub>s removal efficiency from 22 to 72% and COD<sub>dis</sub> removal efficiency from 8 to 35% in all cases tested here, as shown in Figure 2. The removal efficiency was evaluated based on the average data (Table 1). The TSS and COD<sub>T</sub> removal efficiencies were on average 54(±10)% and 47(±9)%, respectively, for the UASB treatment step at and above 6 h HRT. Below 6 h HRT, removal efficiencies dropped significantly to 27(±7)% and 22(±8)% at HRT of 5 and 4 h, respectively, even though the temperature was higher. HRT had no significant influence (p < 0.05) on the COD<sub>T</sub> and TSS removal efficiencies of the UASB reactor at HRT ≥ 6 h, even though other variables were changing (Table 1). This suggests that there is a hydraulic load threshold around HRT = 6 h, below which UASB reactor removal efficiencies deteriorate for the conditions tested. We therefore propose this as a design limit that should be used with caution until more comprehensive tests are carried out.

Pulse feeding stimulates the development of granular sludge with both improved settling and degradation properties (Franco et al. 2003; Rocktäschel et al. 2013). The pulse feeding strategy applied here was confirmed to serve these purposes by the good process performance observed within a few weeks after process start (a continuous-flow gravity-fed reactor, intended as reference case, failed and is therefore not reported). The standard, robust and cheap
Table 1 | Influent and effluent characteristics and % removal efficiencies of UASB and septic tank-UASB combined reactor @ 18 h, 12 h, 8 h, 6 h, 5 h and 4 h HRT

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Septic Tank (ST)</th>
<th>UASB Reactor 18 h HRT</th>
<th>ST-UASB 18 h HRT</th>
<th>UASB Reactor-12 h HRT</th>
<th>ST-UASB 12 h HRT</th>
<th>UASB Reactor 8 h HRT</th>
<th>ST-UASB 8 h HRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS mg/L</td>
<td></td>
<td>800 (390)</td>
<td>335 (172)</td>
<td>63 (13)</td>
<td>491 (164)</td>
<td>57 (8)</td>
<td>75</td>
<td>349 (105)</td>
</tr>
<tr>
<td>CODR mg/L</td>
<td></td>
<td>1,100 (470)</td>
<td>750 (499)</td>
<td>56 (10)</td>
<td>863 (117)</td>
<td>43 (7)</td>
<td>56</td>
<td>742 (204)</td>
</tr>
<tr>
<td>CODdis mg/L</td>
<td></td>
<td>-</td>
<td>231 [1]</td>
<td>35</td>
<td>-</td>
<td>23 (7)</td>
<td>-</td>
<td>261 (88)</td>
</tr>
<tr>
<td>CODss mg/L</td>
<td></td>
<td>-</td>
<td>399 [1]</td>
<td>72</td>
<td>-</td>
<td>52 (12)</td>
<td>-</td>
<td>562 (217)</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>-</td>
<td>17</td>
<td>-</td>
<td>9</td>
<td>-</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>-</td>
<td>7.8</td>
<td>7.4</td>
<td>-</td>
<td>7.4</td>
<td>-</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Standard deviations are given in parentheses. Numbers of samples are given in square brackets. Rem. Ef., removal efficiency.
feed pump set to generate an up-flow velocity of about 1.5 to 2 m/h during each pulse evidently generated sufficient mixing. It was assumed, but not documented, that the sludge settled by gravity between pulses, but slowly, due to biogas generation between each feed pulse. Others have observed that pulse feeding causes proper mixing of organic material present in the feed wastewater with the active sludge bed of UASB reactors (Bergland et al. 2015). It is therefore concluded that the pulse feeding strategy can be a robust and cost-efficient method.

Temperature also influenced pollutant removal efficiencies (Figures 2 and 3), but quite fair removal was maintained even during the coldest periods (12 h HRT at 9°C and 8 h HRT at 13°C). This shows that the plant design investigated is applicable for efficient treatment for all seasons in Kathmandu as long as HRT is not too low, as discussed further below.

The COD mass balance prepared based on influent COD$_T$, effluent COD$_T$ and COD as methane during each HRT of the study period is shown in Figure 3. The difference between the influent COD and the COD out as both effluent and biogas was assumed to accumulate in the system; 3–37% of UASB reactor influent COD$_T$ was converted into methane and recovered as biogas. Some methane always stays dissolved and is lost with effluent water, but this, presumably insignificant, fraction (due to low solubility) was not measured. Of inlet COD$_T$, 12–19% accumulated in the UASB reactor while 44–85% left with the effluent.

The COD accumulation observed implies that the UASB reactor was not truly at steady state, and can be explained at least partly by microbial cell synthesis and accumulation as population adaptation to increasing organic loads. Such sludge blanket culture adaptation to the OLR increase imposed seems reasonable. No additional experimental methods to observe and quantify the granular sludge accumulation were applied. The sludge accumulation suggested that some regular excess sludge removal may be required for long-term stable operation, but this study was too short to quantify such needs.

The fraction converted to methane decreased with lower HRT, but this was not statistically significant at HRT $\geq 6$ h. No hydrolysis and almost no methanogenesis occurred at HRT 4 h. These results show that pulse feeding ST effluents to UASB can serve as a compact secondary wastewater treatment solution. HRT = 6 h with an organic loading rate of about 5kgCOD/m$^2$.d as a safe lower operation limit was not tested for the lowest relevant temperatures. The results
suggest, however, that possible reduced performance at lower temperature would have no detrimental effects.

Hydrolysis and methanogenesis

The average percentages of COD hydrolysis and methanogenesis, calculated according to Equations (2) and (3), for all UASB HRTs tested are shown in Figure 3. Methanogenesis was consistently higher than hydrolysis, implying that hydrolysis was the rate-limiting step for the overall conversion of organic matter to methane for all cases studied here. This is probably a result of ST-treated domestic wastewater composition, relatively low process temperature and HRT. Moreover, it was obvious that both rates declined towards zero at the lowest HRT tested. The methanogenesis in excess of hydrolysis was assumed to be caused by the consumption of organic matter hydrolyzed in the septic tank.

UASB reactor sizing

The UASB reactor performance below 6 h HRT was poor. Using 6 h HRT as a lower design limit, the required volume of a full-scale UASB reactor for this particular case, having a wastewater flow of 15 m³/d from 270 people, is about 4 m³ (=15 m³/d × 0.25d). The per capita UASB volume requirement is, thereby, about 15 L, and about 100 L for the average Nepalese family of six persons. A cheap 250L barrel reactor (cost about 45 USD) design, as applied in this study, would therefore be sufficient for most existing (1 to 2 m³) ST solutions in Nepal. This would give HRT > two times the proposed 6 h design limit, implying high all-year performance.

Table 2 | Comparison between present and previous studies on UASB reactor system for domestic wastewater treatment

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Temperature (°C)</th>
<th>HRT (h)</th>
<th>OLR (kg COD/m³d)</th>
<th>COD T</th>
<th>TSS</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>UASB*</td>
<td>9–22</td>
<td>16–36</td>
<td>–</td>
<td>74–82</td>
<td>67–77</td>
<td>This study</td>
</tr>
<tr>
<td>Septic tank-UASB</td>
<td>9–22</td>
<td>22–36</td>
<td>–</td>
<td>47–71</td>
<td>60–86</td>
<td>This study</td>
</tr>
<tr>
<td>UASB-septic tank</td>
<td>17–34</td>
<td>9–44</td>
<td>0.45, 0.23</td>
<td>51, 54</td>
<td>74, 78</td>
<td>Al-Jamal &amp; Mahmoud (2009)</td>
</tr>
<tr>
<td>UASB-septic tank</td>
<td>&gt;20</td>
<td>32</td>
<td>0.96</td>
<td>67–77</td>
<td>–</td>
<td>Lettinga et al. (1993)</td>
</tr>
<tr>
<td>UASB-septic tank</td>
<td>24</td>
<td>48–96</td>
<td>0.63, 0.32</td>
<td>56, 58</td>
<td>81, 82</td>
<td>Al-Shayah &amp; Mahmoud (2008)</td>
</tr>
</tbody>
</table>

*Pollutant removal efficiency in a UASB reactor alone in the septic tank-UASB combined system.

ST-UASB combination

The TSS and COD T removal efficiencies for the ST-UASB combined system were in the range of 60 to 86% and 47% to 71%, respectively, in all cases tested here (Figure 2). The results from the cases using UASB HRT ≥ 6 h (as recommended above) showed that TSS removal efficiency for the ST-UASB combined system was consistently at least 75%. COD T removal efficiency was at least 55% at HRT ≥ 6 h even at a temperature of 9 °C. Wide use of such treatment solutions can, for example, give a vast improvement of wastewater discharges to the heavily polluted rivers of Kathmandu.

Comparison with other studies

The removal efficiencies of pollutants, measured as COD T and TSS, attained in this study for varying OLR and HRT was in the upper ranges reported for other full- and pilot-scale plants using UASB-based reactor processes to treat domestic wastewater (Table 2). Al-Shayah & Mahmoud (2008) reported UASB-ST TSS and COD T removal of 81% (range 76–86%) and 56% (range 45–72%), respectively, for 48 h HRT and 82% (range 76–87%) and 58% (range 48–77%), respectively, for 96 h HRT operating at 24° C with OLR of 0.32 and 0.63 kg COD/m³d. Halalsheh (2005) reported 58% (range 51–62%) COD T removal in a full-scale conventional UASB reactor (60 m³) at an average of 25 °C and 24 h HRT. Al-Jamal & Mahmoud (2009) reported 51% and 54% COD T removal at 48 h and 96 h HRT and 0.45 and 0.23 kg COD/m³d OLR and at temperatures of 17–34 °C. Lettinga et al. (1993) reported 66–77% COD T removal at 32 h HRT with 0.96 kg COD/m³d.
OLR and at $T > 20^\circ C$. Mahmoud (2008) reported 44% COD\textsubscript{T} removal for UASB reactor at 6 h HRT and 15 $^\circ C$ wastewater.

The ST-UASB combined system studied here performed well compared with these published cases. The main differences were that the present study operated at lower temperatures and/or higher hydraulic and organic loads, while maintaining similar COD and TSS removal to those published by others. The implication of this is that cheap solutions with low physical footprints can be used, making extensive dissemination of such solutions realistic.

CONCLUSION

Removal efficiencies of TSS, COD\textsubscript{T}, COD\textsubscript{dis} and COD\textsubscript{ds} in the UASB were 44–63%, 39–56%, 23–35% and 46–72% respectively, at HRT above 6 h.

The ST-UASB combined pilot plant gave efficient anaerobic wastewater treatment with COD\textsubscript{T} and TSS removal of 55–71% and 75–86%, respectively. This removal is in the upper range reported by others for other types of UASB-based domestic wastewater treatment and achieved at higher loads.

About 1/7 of influent COD accumulated in the reactor, 1/3 was converted to and recovered as methane, and the rest was released with the effluent.

UASB performance dropped at HRT < 6 h, while stable performance was established at HRT at and above 6 h. Temperature influences the process performance, but it worked well even at the lowest temperature (9 $^\circ C$) tested.

ST-UASB combined systems can be a sustainable sanitation option.

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REFERENCES


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