Anaerobic biodegradability and digestion in accumulation systems for concentrated black water and kitchen organic-wastes


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Abstract

The feasibility of two accumulation-systems (AC) for anaerobic digestion and storage of concentrated black water with (AC1) or without (AC2) urine + kitchen organic-wastes was investigated. The waste(water) was collected by two vacuum toilet/transport systems. The influent-total COD of the AC2 (53,000 mg/L) was more concentrated by four times than that of the AC1. The suspended COD represented the major part (71–73%) of influent total COD of the two systems. The batch-experiments results showed a high anaerobic biodegradability of the waste(water) (> 85%). The AC systems demonstrated stable performance. There was no inhibition effect of NH4 and VFA concentration decreased in time. Total COD removal of 58% was achieved in both systems, after 105 days at 20°C. Moreover, if only the supernatant in AC1 is withdrawn and the settled sludge stays for the next runs, only 20% of the influent total COD will be in the supernatant. In AC2, 74% of influent ortho-P was removed by precipitation. Therefore, the settled sludge in the AC2 had a high total-P concentration of 1,300 mg/L. The C:N:P ratios of the supernatant and the sludge were 26:13:1 and 35:4:5:1, respectively, in the AC1, and were 28:14:1 and 32:2:4:1, respectively, in AC2.

Keywords Anaerobic digestion; biodegradability; black water; decentralised treatment; kitchen organic-wastes

Introduction

The existing paradigm for transport and centralised treatment of municipal waste(water) is not a sustainable solution. In this concept, the waste(water) is considered as a pollutant, while in the decentralised concept, the waste(water) is used as a resource for fertiliser, water and even energy and for closing water and nutrient cycles (Wilderer and Schreff, 2000; Otterpohl et al., 2003). The decentralised treatment of municipal waste(water) based on separation between grey and black water, and even between faeces and urine, represents a sustainable and future solution for waste(water) treatment. Most of organic matters, nutrients and pathogens in the municipal wastewater originate from the black water, which represents only 20–30% of the volume of municipal wastewater (Otterpohl et al., 1999; Zeeman and Lettinga, 1999). Anaerobic digestion symbolises a sustainable and low-cost technology for waste(water) treatment. Therefore, it is profitable to apply anaerobic digestion within the decentralised sanitation.

In accumulation (AC) systems anaerobic-digestion and storage of waste(water) are combined in one reactor (Zeeman, 1991). At low temperatures, like in Western Europe, it is forbidden to apply fertilisers on the field during the winter period. Therefore, a storage period of 3–6 months for AC systems is necessary to overcome the winter period. In that situation, combined storage and anaerobic digestion in the AC system at ambient temperatures is a feasible alternative for a completely stirred tank reactor. The digested waste(water) in the AC system can be applied after the storage period on the fields as a
fertiliser. The application potential of the AC system for black-water treatment improves at increasing the concentration of black water. This can be achieved with the reduction of the amount of water used for toilet flushing. Application of vacuum toilets, which are normally used in aeroplanes and ships, can result in a huge reduction of water used for toilet flushing. Conventional toilets consume 7–9 L/flush, while vacuum toilets only consume 0.7–1.0 L/flush. In addition to black water, the AC system can also digest kitchen organic-wastes, which will also improve the potential of the utilisation of biogas produced from the AC system, as the kitchen organic-wastes have a high-organic content.

The aims of this research are: (1) study the performance of two AC systems treating concentrated black water (collected by vacuum toilet/transport system; with and without urine) + kitchen organic-wastes for a period of 105 days at a controlled temperature of 20°C; (2) determination of the anaerobic biodegradability and hydrolysis constant ($K_h$) of the concentrated black water (with and without urine) + kitchen organic-wastes at temperatures of 20 and 30°C.

**Materials and methods**

**Experimental set-up**

Two identical accumulation reactors (AC1 and AC2) were connected to two vacuum toilets/transport systems (Roediger, Germany), as shown in **Figure 1**. Each vacuum system consisted of a vacuum toilet, vacuum pump, 10 L equalisation tank and waste(water) pump. Each AC system was a closed tank made of polyethylene with height, diameter and maximum volume of 1.6 m, 0.984 m and 1.22 m$^3$, respectively. The headspace of each AC system was connected to a gas meter. In the reactor wall at equal distance of 0.2 m, six taps were mounted, for having waste(water) samples. The AC systems were installed in the Experimental Hall of Bennekom, The Netherlands. The systems were fed with the faeces and urine of the employees in the Hall, while the kitchen organic-wastes were collected from the Ede Hospital, The Netherlands. The difference between the two AC systems was the amount of urine. The AC2 system received less urine (only the urine produced during defecation). For obtaining the real influent-waste(water) quantity and revising the assumed flow, every person using the toilet was requested to fill a special form on the type of the provided waste(water) (i.e. faeces, urine or extra flushing).

The AC systems were installed at a controlled-temperature room, adjusted at a temperature of 20°C. It is assumed within the decentralised-treatment concept that the AC...
system can be placed in the cellar of any building. Therefore, such temperature can be relatively secured for the whole duration of the year. The two AC systems were seeded by 137 and 167 litres of sludge adapted with the same waste(water) for a period of 150 days of operation (Kujawa-Roeleveld et al., 2003) followed by 70 days storage at 20°C.

**Wastewater biodegradability and sludge digestibility experiments**

Anaerobic biodegradability and hydrolysis constant ($K_h$) at a temperature of 20 and 30°C were determined for the influent waste(water) of AC1 and AC2 in batch tests (in a series of closed serum-bottles of 0.5 L). The methane production and COD fractions were determined as a function of time. For having representative values, the biodegradability and $K_h$ were determined twice for two different influent samples. The experiments were performed by addition of inoculum to the waste(water). Blank samples with only inoculum were used for determination of the net values. For determination of the remaining biodegradable fraction in the waste(water) in the AC systems at the end of the experiment, additional anaerobic digestibility tests were performed in closed serum bottles at 30°C. The digestibility was carried out for the waste(water) from each tap in each reactor. The digestibility tests were carried out for digestion period of 215 days for the waste(water) of the AC systems.

**Waste(water) sampling**

For characterisation of the influent black water (without kitchen organic-wastes) of the AC systems, grab samples were taken from the content of the equalization tank, before kitchen-wastes addition. The composition of the kitchen organic-wastes was measured separately. A mixture of equal-volume grab-samples taken from the taps in each reactor represented the content of each AC system. At the end of the experiment, the characteristics of the waste(water) from each tap in both AC systems were determined separately.

**Analysis**

COD was determined as described by Standard Methods (APHA, 1998). Raw samples were used for total COD (COD$_t$), 4.4 μm folded paper-filtered (Schleicher & Schuell 5951/2) samples for COD$_f$ and 0.45 μm membrane-filtered (Schleicher & Schuell ME 25) samples for dissolved COD (COD$_{dis}$). The suspended COD (COD$_{sus}$) and colloidal COD (COD$_{col}$) were calculated by the differences between COD$_t$ and COD$_f$, COD$_f$ and COD$_{dis}$, respectively. Volatile fatty acids (VFA) were measured from membrane-filtered samples with a gas chromatograph, as described by Lier (1995). The biogas composition CH$_4$, CO$_2$, N$_2$ and O$_2$ was determined in a 100 μl sample using a gas chromatograph, described by Lier (1995). The Kjeldahl nitrogen (Kj-N) was measured according to the Dutch Standard Normalized Methods, DSNM (1969). Total PO$_4$–P for waste(water) was measured with an auto analyser (Skalar) after treatment according to DSNM (1969), while NH$_4^+$-N and ortho PO$_4$-P were directly measured with the same auto analyser.

**Calculations**

The hydrolysis constant ($K_h$) in the batch experiments and the percentages of hydrolysis (H), acidification (A) and methanogenesis (M) in each AC system at the end
of the experiment were calculated according to Equations 1, 2, 3 and 4, respectively.

\[ \ln(S_t/S_0) = -k_h \times t \]  

(1)

\[ H = 100 \left( \frac{\text{acc. CH}_4 \text{as COD/V} + \text{COD}_{\text{dis}} \text{in the system at the end} - \text{influent COD}_{\text{dis}}}{\text{influent COD}_{\text{ss}} + \text{influent COD}_{\text{col}}} \right) \]  

(2)

\[ A = 100 \left( \frac{\text{acc. CH}_4 \text{as COD/V} + \text{VFA as COD} \text{in the system at the end} - \text{influent VFA as COD}}{\text{influent COD}_{t} - \text{influent VFA as COD}} \right) \]  

(3)

\[ M(\%) = 100 \left( \frac{\text{CH}_4 \text{as COD}}{\text{influent COD}_{t}} \right) \]  

(4)

where:

- \( S_0 \) = accumulated \( \text{CH}_4 \) at time \( t = \text{end} \) + \( \text{COD}_{\text{dis}} \) at \( t = \text{end} - \text{COD}_{\text{dis}} \) at \( t = 0 \);

- \( S_t = S_0 - (\text{accumulated CH}_4 \text{at } t = 1 + \text{COD}_{\text{dis}} \text{at } t = 1 - \text{COD}_{\text{dis}} \text{at } t = 0) \);

- \( V \) = total volume of the waste(water) entering each AC system.

Results and discussion

Anaerobic biodegradability of the waste(water)

Table 1 showed the maximum anaerobic biodegradability and the \( K_h \) (d\(^{-1}\)) values for the influent waste(water) of AC1 and AC2 at temperatures of 20 and 30°C. The results clearly showed high and almost similar anaerobic biodegradability of the influent waste(water) of both AC systems. These values (85–96%) are higher than those found by Elmitwalli et al. (2001), Halalsheh (2002) and Elmitwalli et al. (2003) for, respectively, Dutch black water (71%), Jordanian sewage (76–78%) and Egyptian sewage (66–73%). Addition of kitchen organic-wastes might be the reason for such high biodegradability. The values of \( K_h \) are also slightly higher than that found by Mahmoud (2002) for Dutch primary sludge, 0.07 d\(^{-1}\) at 25°C.

AC systems performance

Influent waste(water) characteristics. The results showed that the average, maximum and minimum influent waste(water) volumes per week were, respectively, 33.9, 56.3 and 15.8 litres/week for AC1 system and, respectively, 21.4, 36.1 and 4.4 litres/week for AC2 system. This indicates that both AC systems were exposed to high flow-variation. Table 2 presents the characteristics of the influent black water and the influent waste(water) (black water + kitchen organic-wastes) for the AC systems. The influent total COD was more concentrated by four times in the AC2 system than that of the AC1 system and the influent Kj-N and total P were higher in the AC2 system by 1.5 and 3 times, respectively. The results showed that the suspended COD represented the major part of the total COD.

Table 1 The maximum anaerobic biodegradability of the influent waste(water) of AC1 and AC2 systems at temperatures of 20 and 30°C

<table>
<thead>
<tr>
<th>System</th>
<th>Anaerobic biodegradability (%)</th>
<th>( K_h ) (1/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AC1 20°C 30°C AC2 20°C 30°C</td>
<td>AC1 20°C 30°C AC2 20°C 30°C</td>
</tr>
<tr>
<td>Batch 1</td>
<td>82 84 68 92</td>
<td>0.13 0.14 0.09 0.12</td>
</tr>
<tr>
<td>Batch 2</td>
<td>81 85 96 91</td>
<td>0.09 0.12 0.10 0.10</td>
</tr>
</tbody>
</table>
influent-COD in both AC systems (71–73%) and the colloidal COD represented the lowest COD fraction (<2% of the total COD) in the influent wastewater of both systems. The percentage of suspended COD in black water (71–73%) is higher than that in the raw sewage (38–43%, Elmitwalli et al., 2002), while the black water contains a lower fraction of colloidal COD, as compared to that of sewage (25–30%, Elmitwalli et al., 2002). The percentage of dissolved COD seems to be similar in both black water and sewage (about 30% of total COD).

Characteristics of the waste(water) accumulated in the systems. Figure 2 presents the course of COD fractions, nutrients and pH in the AC systems. The results of both AC systems showed stable performance, especially after 40 days of operation. There was no inhibition effect of NH₄ and VFA concentration decreased in time in both systems (i.e. no VFA accumulation). Also, the pH values ranged between 7.2 and 7.6. After 105 days of operation, the average total COD concentration was 7,800 and 22,800 mg/L.
in, respectively, the AC1 and AC2 system. Accordingly, the total COD removal in the AC systems was 58% for both reactors.

Contrary to the results of total COD, the nutrients concentration in the AC systems after 105 days of operation were higher than that of the influent waste(water), mainly due to higher nutrients concentration in the inoculum, as compared to that in the influent. The ortho PO$_4$ content (80 mg/L) in the AC2 after 105 days of operation was significantly lower than the ortho PO$_4$ in the influent waste(water) (311 mg/L). The high removal of the ortho PO$_4$ (74%) in AC2 system might be due to the formation of complexes, like struvite (MgNH$_4$PO$_4$) (Loewenthal et al., 1994). The latter will lead to an increase of the total P content of the sludge in the bottom of the system. This is confirmed by the experimental results. The total-P concentration of sludge in the bottom of the AC2 system after an operational period of 105 days was 1,310 mg/L, while that of the seed sludge amounted to 790 mg/L. The results showed that the total COD:Kj-N: total P (C:N:P) ratio of the sludge in the bottom of the AC systems changed with operational time. The C:N:P ratios for influent waste(water), seed sludge and the sludge in the bottom of the AC system after operational period of 105 days were, respectively, 170:11:1, 72:6.5:1 and 35:4.5:1 for AC1 system and were, respectively, 153:5.4:1, 37:3.8:1 and 32:2.4:1 for AC2 system.

Waste(water) profile in the AC systems at the end of the accumulation period. Table 3 presents the profile of pH, COD fractions, and nutrients (N and P) in the AC system after an operational period of 105 days. The total COD profile in the AC1 system indicated that there was poor mixing in the systems (especially in AC1 system), as the sludge occupied only the lowest part of the system. The mixing occurred in the AC systems by the produced biogas and by pumping of the influent waste(water). The waste(water) supernatant of the AC1 and AC2 (from tap 2) had a low total COD concentration (3,500 and 4,800 mg/L, respectively), as compared to the wastewater concentration in the bottom of the reactors, due to settling of particulates.

Biogas production. The results indicated that the composition of the produced biogas from both AC systems was similar (70% methane and 30% carbon dioxide). Figure 3 shows the course of the daily biogas production and the accumulated methane-production in AC systems. It seems that there was a biogas leakage in the biogas measuring line, as the biogas production started after 49 and 31 days of operation of AC1 and AC2 system, respectively. The results showed higher values for H, A and M in AC2 system (46, 44 and 53%, respectively), as compared to those in AC1 system (22, 19 and 28%, respectively). However, the course of COD and VFA concentrations (Figure 2A and B) showed that significant amounts of total COD and VFA were removed in both systems in

Table 3 The profile of pH, COD fractions, and nutrients (N and P) in the AC system after an operational period of 105 days

<table>
<thead>
<tr>
<th>System</th>
<th>Tap</th>
<th>pH</th>
<th>COD (mg/L)</th>
<th>Kj-N (mg/L)</th>
<th>NH$_4$-N (mg/L)</th>
<th>Total P (mg/L)</th>
<th>PO$_4$-P (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>Suspended + colloidal</td>
<td>Dissolved</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC1</td>
<td>1</td>
<td>7.33</td>
<td>20,400</td>
<td>19,200</td>
<td>1,020</td>
<td>2,630</td>
<td>3,130</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.37</td>
<td>3,400</td>
<td>2,300</td>
<td>960</td>
<td>1,750</td>
<td>1,160</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.43</td>
<td>3,500</td>
<td>2,100</td>
<td>1,180</td>
<td>1,760</td>
<td>1,210</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7.51</td>
<td>3,600</td>
<td>2,000</td>
<td>1,300</td>
<td>1,700</td>
<td>1,440</td>
</tr>
<tr>
<td>AC2</td>
<td>1</td>
<td>7.58</td>
<td>42,000</td>
<td>40,300</td>
<td>1,600</td>
<td>3,120</td>
<td>1,650</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.48</td>
<td>4,800</td>
<td>2,700</td>
<td>1,500</td>
<td>2,440</td>
<td>1,620</td>
</tr>
</tbody>
</table>
the first month of operation. After 105 days of operation, the total COD removal was similar in both systems and amounted to 58%. The high difference between M (28%) and total COD removal (58%) in the AC1 system after 105 days of operation confirms the assumption of biogas leakage in the line of measuring of biogas production. In the AC2 systems, the biogas leakage was small, as the difference between M and total COD removal was only 5%.

Digestibility of the accumulated waste(water) in the AC systems. The digestibility results showed that a relatively high amount of biodegradable particulates remained in the AC1 system (30%), while it was only 8% for AC2 system. However, these values represented only 11 and 4% of the total COD added to, respectively, AC1 and AC2 system.

Discussion
The high anaerobic biodegradability of the black water + kitchen organic-wastes (>85%) demonstrates the high potential of application of the anaerobic digestion. Moreover, the AC system, which is a low-cost system for anaerobic digestion + storage of the waste(water), was an efficient system for anaerobic digestion of the waste(water). In the two AC systems, 58% of the total COD was removed after an operational period of 105 days at 20°C. In the AC1 system, most of particulates were settled in the bottom of the system and occupied about 20% of the waste(water) volume in the tank after 105 days of operation. The settled solids are almost the required amount of the seed sludge for the next cycle of feed. Accordingly, the supernatant needs only to be withdrawn from the AC system. The supernatant in the AC1 system after 105 days of operation had a low total COD concentration (about 3,500 mg/L, Table 3) corresponding to 80% total COD removal. The withdrawal of the supernatant from the AC system after each cycle of feeding will: (a) increase the residence time of particulates in the system, which will lead to increase the hydrolysis of particulates and biogas production, (b) improve the application of the digested waste(water) in the AC system as a fertiliser. There will be two types of waste(water) streams discharged from the system, the supernatant and the sludge in the bottom. The C:N:P are different for each stream. In AC1 system, the C:N:P ratios were 26:13:1 and 35:4.5:1 for the supernatant and the sludge, respectively, and in AC2 system, the ratios were 28:14:1 and 32:2.4:1, respectively. The sludge had a higher total P content, as compared to the supernatant and the sludge of the AC2 system had the highest total P content.
The experimental results reveal that the separation between concentrate and dilute municipal waste (water) streams and the water consumption reduction in toilet flushing are not only suitable for ecological sanitation, but also for centralised sanitation. For the concentrated stream in the centralised sanitation, high removal of COD, P and N can be achieved by relatively low-cost technology. COD can be removed by anaerobic digestion and a significant part of P will be removed by precipitation in the digester, while N removal can be obtained by application of Sharon/Anammox systems.

Conclusions
The results of batch experiments showed a high maximum-anaerobic biodegradability of the influent waste (water) (> 85%). The operational results of the two AC systems demonstrated that total COD removal of 58% was achieved in both systems after an operational period of 105 days at 20°C. Moreover, if only the supernatant in AC1 system is withdrawn and the settled sludge stays for the next runs, only 20% of the influent total COD will remain in the supernatant.

In the AC2 system, 74% of influent ortho-P was removed by precipitation. Therefore, the settled sludge in the bottom of AC2 system had a high total P concentration of 1,300 mg/L at the end of the experiments.

In the AC1 system, the C:N:P ratios were 26:13:1 and 35:4.5:1 for the supernatant and the sludge, respectively, and in AC2 system, the ratios were 28:14:1 and 32:2.4:1, respectively.

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References

