Effect of organic loading rate on the performance of two-stage anaerobic digestion of the organic fraction of municipal solid waste (OFMSW)

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ABSTRACT

Two-stage anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) was carried out: hydrolysis and acidogenesis in a continuous anaerobic hydrolytic leach bed (AHLB) reactor loaded at different rates (Bv, = 3.8–7 gVSS L⁻¹ d⁻¹) and methanogenesis of leachates, diluted with municipal wastewater, in an upflow anaerobic sludge blanket (UASB) reactor at organic loading rates of 6.6–13 gCOD L⁻¹ d⁻¹. In the AHLB reactor, 51–76% and 58–71% volatile solids and chemical oxygen demand (COD) removal efficiencies were obtained. During the hydrolysis and acidogenesis phases, the effluents were at pH 4.93, the leachate had a volatile fatty acids concentration of 35 g/L and the biogas was composed only of CO₂. The average methane production in the UASB in the load of 4.4 gVS L⁻¹ d⁻¹ in the AHLB was 3.32 LCH₄ L⁻¹ d⁻¹ (YCH₄ = 80%), with COD removal efficiency of 95% and methane yield 279 LCH₄ KgVSSOFMSW degraded.

Key words | hydrolysis, leachate, methanogenesis, OFMSW (organic fraction of municipal solid waste)

INTRODUCTION

Two-stage anaerobic digestion (TSAD) is effective for residues with high organic content, which can ferment easily (Bouallagui et al. 2005). The physical separation of the hydrolytic-acidogenic and methanogenic phases allows for setting up the best conditions for each of the microbial groups involved (Cirne et al. 2007); biopolymer (proteins, lipids, starches) by enzymatic hydrolysis and acidogenesis yield pH near to the pKa of volatile fatty acids (Ince 1998), while a neutral pH is needed to produce methane. The organic fraction of municipal solid wastes (OFMSW) has 15–20% of easily fermentable volatile solids (VS) with 1.06 g chemical oxygen demand (COD)/g VS (Browne et al. 2013; Browne & Murphy 2014; Ramirez et al. 2014); thus it is a suitable substrate for TSAD. The feed to the first acidogenic reactor can be ‘dry’ at the normal OFMSW water content of 80% or less (Xu et al. 2011; Tran et al. 2011; Browne et al. 2015; Browne & Murphy 2014) and ‘wet’ with total solids of less than 20% (Bouallagui et al. 2004; Shen et al. 2013). The main reactor configurations are leach bed and stirred tank reactors, respectively, and an upflow anaerobic sludge blanket (UASB) reactor for methanogenesis (Table 1). The broad line separating dry and wet fermentation is between 20 and 10% solids. A variation is two stirred tanks in series (Shen et al. 2013; Bo & Pin-Jing 2014). Most of the dry processes uses leach bed reactors (Tran & Palenzuela 2012; Browne & Murphy 2014; Ramirez et al. 2014). A variation is the Ramirez et al. (2014) process, which combines wastewater and OFMSW anaerobic treatments.

To accelerate the hydrolysis of OFMSW, some authors recirculate a fraction of leachate mixed with water (Xu et al. 2011) or with effluent from the UASB in order to increase the hydrolysis, pH and buffering capacity in the first step (Stabnikova et al. 2008; Tran & Palenzuela 2012; Bo & Pin-Jing 2014; Browne & Murphy 2014).

The aim of this work was to test OFMSW from the university campus cafeteria, separating the hydrolysis and acidogenesis in a continuous hydrolytic anaerobic slurred bed, and the generated leachate diluted with municipal wastewater for the production of biogas in a UASB reactor.
MATERIALS AND METHODS

AHLB and UASB reactors

The anaerobic hydrolytic leach bed (AHLB) reactor consisted of an 8 L glass column, 14.5 cm internal diameter, 60 cm height, with a conical bottom (Figure 1). It was fed from the top with a weighed amount of OFMSW and 200 mL/d of the UASB effluent; it was started with 1 kg of digested OFMSW from previous batch tests (pH 4.14, 14% total solids (TS), 12% VS, 16% COD/TS, protein, 6% P/TS and carbohydrates 1% carbohydrates/TS (Ramírez et al. 2014). It was fed with the OFMSW at different solids loading rates (SLR), 3.8, 4.4, 4.4 (with R = 0.1), 6 and 7 (R = 0.2) g VS L⁻¹ d⁻¹. The UASB reactor consisted of a glass column (0.95 L), inoculated with 320 mL of granular sludge (52 gVSS L⁻¹), from a UASB reactor treating leachates. It was fed at different organic loading rates (OLR g COD L⁻¹ d⁻¹) depending on the AHLB reactor results. The response variables were: pH, solids, protein, COD, volatile fatty acids (VFA) and carbohydrates in both the OFMSW and the leachate and the generated biogas.

System description

The OFMSW was fed to the continuous AHLB reactor at W₀ (g VS d⁻¹) and the digested solids are withdrawn at W₁. The fermenting mass A is sprinkled with the effluent of a UASB reactor treating leachates (Fᵢₑ, Sᵢₑ) and municipal wastewater (Fᵢₚₑ, Sᵢₚₑ) at a flow rate (Fᵢₑ = 200 mL/d) given by a dilution rate of 0.025 L/Lr d. The mixture of municipal wastewater (MWW) and leachates yield the reactor feed (Fᵢₒₑ, Sᵢₒₑ), which is converted to methane (QCH₄) and an effluent (Fᵢₑ, Sᵢₑ). In some experimental runs, part of the leachate was recycled (R*Fᵢₑ) to the AHLB.

Mass balances

The global COD balance shows the methane contribution from both the OFMSW and the MWW (Equation (1)):

\[
\frac{dW}{dt} = W₀X₀S₀ + Fᵢₑ XₑSₑ - W₁X₁S₁ - Fᵢₚₑ XₚₑSₚₑ - VₐQ₁CH₄\frac{V₁CH₄}{YCH₄} = 0
\]

(1)

From the VS balance in the AHLB, the hydrolysis constant k was obtained from Equation (2).

\[
\frac{dS₀}{dt} = W₀S₀ - W₁S₁ - V₁S₁ = 0
\]

(2)

\[
k = \frac{(W₀S₀ - W₁S₁)}{VₐS₁}
\]

COD and VS balances in the AHLB reactor

\[
\frac{dS}{dt} = (W₀S₀ + FᵢₑSₑ) - W₁Xₛ₁ + Fᵢₚₑ(Sₚₑ - Cₚₑ - Cₛₑ) - V₁S₁
\]

(3)

\[
r₁ = \frac{(W₀S₀ - W₁S₁)}{Vₐ} - Dₐ(Cₚₑ - Cₛₑ).
\]
At the UASB:

\[ F_U S_{U0} - F_U S_U - \frac{V_L Q_{CH4}}{2CH4} = 0 \]

\[ Q_{CH4} = D_U (S_{U0} - S_U) Y_{2CH4} \]

where subindexes (i): 0 inlet, 1 outlet; U: UASB; A: AHLB; m: municipal wastewater; L: leachate; W: mass (g OFMSW/d); \( X_S \) is COD at OFMWS (gCOD g\(^{-1}\)); \( F \) is flow rate (L d\(^{-1}\)); \( S \) is COD MWW (gCOD L\(^{-1}\)); \( V \) is the reactor volume (L); \( Q_{CH4} \) is methane volume (L); \( Y_{CH4} \) is yield (LCH4/gVS); \( S_P \) is the VS concentration in OFMSW (g g\(^{-1}\)); \( h \) is the hydrolysis rate constant (d\(^{-1}\)); \( Y_2 \) is methane yield (LCH4/kg VS); \( r_i \) degradation rates (g L\(^{-1}\) d\(^{-1}\)).

**Characterization of the OFMSW and MWW**

The OFMSW was collected daily from the cafeteria of the Metropolitan Autonomous University Iztapalapa (MAU-I), milled and crushed to a particle size between 1 and 5 mm. and analyzed for pH, solids, COD, proteins, carbohydrates and lipids. MWW was taken from the university sewer.

**Analytical methods**

The COD, proteins and carbohydrates of OFMSW were determined by suspending one gram of OFMSW in 100 mL of distilled water. Lipids were determined by taking 2 g of dry solids.

For VFA: a sample of 1.5 mL of leachate was centrifuged at 1,120 G for 15 minutes. The obtained supernatant was filtered across a nitrocellulose membrane (Millipore 0.45 μm) taking a 1 mL aliquot, and filled up to 50 mL with distilled water, then an aliquot of 950 μL was acidified with 50 μL of 2.2 M HCl.

For Elemental analysis of the OFMSW: a 10 g sample was dried at 60 °C, broken to a particle size of 0.149 mm and between 2 and 3 mg of sample was burned in the Perkin Elmer model PE 2400 series II (Waltham, MA, USA), at combustion, reduction and detector temperatures of 925 °C, 640 °C and 82.5 °C, respectively, using helium/ hydrogen as transport gases.

The generated biogas volume was measured by a brine (NaCl, 250 g L\(^{-1}\)) column displacement.

Alkalinity, COD, TS, VS, lipids and pH were determined by *Standard Methods* (APHA, AWWA, WPFC 2005). Carbohydrates and proteins were determined by colorimetric techniques (Lowry et al. 1951; Dubois et al. 1956). The VFA determination was carried out in a gas chromatograph HP 5890 (Agilent, Santa Clara, CA, USA) with flame ionization detector with a capillary column AT 1000 using nitrogen as gas carrier to 5 mL min\(^{-1}\); the temperature of the detector and injector were 200 °C, with a ramp of 25 °C min\(^{-1}\).

Biogas composition was determined using a gas chromatograph (GowMAC 580 series, Gow-Mac Inc., Bethlehem, PA, USA) with a thermal conductivity detector operating at a polarity of 120 mA with a Carbosphere 80/100 packed column. The temperatures of the column, detector and injector were: 140 °C, 190 °C, and 170 °C, respectively, with a ramp of 25 °C min\(^{-1}\), using helium as transport gas (25 mL min\(^{-1}\) at 40 psi).

**Statistical analysis**

An analysis of variance (ANOVA) test of means was carried out using Tukey-Kramer at a significance level \( \alpha \) of 0.05.

**RESULTS AND DISCUSSION**

**Characterization of the OFMSW**

MWW and OFMSW were characterized (Table 2) and the results show their large variability due to the fact that they were taken fresh every day. The average moisture content of the OFMSW was 82%, similar to that reported by Wang et al. (2006) and Hernández et al. (2008) for mixtures of kitchen and dining room residues. COD shows the maximum capacity for methane production, yielding 171 gCOD/kg OFMSW, while the wastewater contribution was negligible.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>OFMSW (W0) g L(^{-1})</th>
<th>MWW (Fm) g L(^{-1})</th>
<th>Digestate (W1) g L(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS</td>
<td>18 ± 6</td>
<td>0.17 ± 0.02</td>
<td>10 ± 7.7</td>
</tr>
<tr>
<td>VS</td>
<td>16 ± 6</td>
<td>0</td>
<td>8 ± 3.4</td>
</tr>
<tr>
<td>COD/TS</td>
<td>95 ± 37</td>
<td>0.34 ± 0.16</td>
<td>13.4 ± 4.9</td>
</tr>
<tr>
<td>Protein (Pr/TS)</td>
<td>39 ± 27</td>
<td>0</td>
<td>1.4 ± 0.8</td>
</tr>
<tr>
<td>Carbohydrates (Ch/TS)</td>
<td>55 ± 44</td>
<td>0</td>
<td>0.2 ± 0.02</td>
</tr>
<tr>
<td>Lipids (Lp/TS)</td>
<td>13 ± 9</td>
<td>0</td>
<td>8 ± 5</td>
</tr>
<tr>
<td>VFA</td>
<td>N.D.</td>
<td>0.16 ± 0.005</td>
<td>N.D.</td>
</tr>
<tr>
<td>Ammonium</td>
<td>N.D.</td>
<td>0.24 ± 0.08</td>
<td>N.D.</td>
</tr>
<tr>
<td>C/N</td>
<td>12 ± 2</td>
<td>N.D.</td>
<td>9.8 ± 1.7</td>
</tr>
<tr>
<td>pH</td>
<td>5.7 ± 0.5</td>
<td>8.2 ± 0.3</td>
<td>4.9 ± 0.6</td>
</tr>
</tbody>
</table>

N.D. Not determined.
Some parameters, such as the elementary analysis and C/N relation, are similar to those reported elsewhere (Zhang et al. 2007; Xu et al. 2011; Nagao et al. 2012), and the proteins, carbohydrates and lipids in the kitchen residues reported by Bo & Pin-Jing (2014) and Zhang et al. (2005).

Generally, a C/N ratio range of 20–30 was considered to be the optimum condition for anaerobic digestion (Poyuelo et al. 2011), but recent studies have pointed out that anaerobic digestion performed well at lower C/N ratios of 15–20 (Zhang et al. 2014).

Removal of VS at the AHLB

The VS profile, the COD and VFA throughout the whole study show dependence on the average SLR (Figure 2(a) and 2(b)). The VS output is relatively constant at about 25%, irrespective of the large variation at the inlet.

Table 3 shows the AHLB reactor performance at the SLR that was tested. At increasing SLR, the VS and COD removal efficiencies and VFA production rates increase to a maximum of 79%, 71% and 0.213 g L⁻¹ d⁻¹, respectively. The pH, for the first four runs, remains at an average of 4.93 ± 0.56, which is lower than the initial value, due to the acidogenic conditions producing VFA and a biogas of 100% CO₂ (Selvam et al. 2010; Ramirez et al. 2014). The hydrolysis rate constant k, can be found per each of the different runs by means of Equation (2). The average value is 0.027 ± 0.018 d⁻¹, which is an acceptable value for all runs.

The recycle ratio R shows no clear influence on the performance as it was masked by the increase to an SLR of 6 gVS L⁻¹ d⁻¹. Xu et al. (2011) recycled 50% of the leachates diluted with water and a percolating agent to obtain 63% solids removal.

The last run shows a probable reactor breakdown as the pH drops to 3.9 and the removal efficiencies drop to 53 and 45%, as well as the VFA production rate, as reported by Browne & Murphy (2014). By increasing the SLR, the VFA production rate increases in the leachate, as also found by Bouallagui et al. (2004), mainly acetic (63%) and butyric (18%) acids, (as with Jian et al. 2012), except in the last load when the propionic acid increases (29%) and the total VFA production decreases to 61%, causing a loss in VS and COD removal efficiencies as also observed by Shen et al. (2013).

Methanogenesis in the UASB reactor

The leachate was mixed with MWW to be fed to a UASB reactor as a practice to treat both OFMSW and MWW, a practice that can be innovated in future for other cities. Figure 3 shows the OLR evolution through the experiments. It shows that the COD removal efficiencies were higher than 90%, working at alkalinity ratios higher than 0.6, with methane production rates increasing with organic loading rate. Adaption periods in each run varied, but the data were obtained in a pseudo steady state (more than 5 HRT with constant values). The HRT was of 1 day for the 3 first runs. In run 3, the OLR decreased to 7 because part of the leachates were used in recirculation to the AHLB. The next experiments were run at 9 and 13 by decreasing HRT to 0.5 d.

Table 4 shows the performance of the UASB reactor at the different SLR in the AHLB reactor by combining MWW with leachates and HRT distinct OLR (6–13 gCOD L⁻¹ d⁻¹) in the UASB.

It is observed that although the optimum SLR to obtain a better solids destruction is 6, when the UASB is integrated, the best loading rate is 4.4.

In this study, we obtained removal efficiencies for COD of 95%, above that obtained by Zhang et al. (2005), Shen
Table 3 | AHLB reactor performance at different SLR

<table>
<thead>
<tr>
<th>SLR (gVS L$^{-1}$ d$^{-1}$)</th>
<th>$W_1$ pH</th>
<th>$K$ (d$^{-1}$)</th>
<th>$\eta_{VS}$ (%)</th>
<th>$\eta_{COD}$ (%)</th>
<th>$V_{RVA}$ (g L$^{-1}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8 ± 0.70</td>
<td>4.86 ± 0.63$^{ab}$</td>
<td>0.018</td>
<td>63 ± 10.6$^{ab}$</td>
<td>58 ± 15.6$^{ab}$</td>
<td>0.074 ± 0.01$^a$</td>
</tr>
<tr>
<td>4.4 ± 0.19</td>
<td>5.22 ± 0.35$^{b}$</td>
<td>0.028</td>
<td>77 ± 3.6$^b$</td>
<td>58 ± 2.1$^{ab}$</td>
<td>0.175 ± 0.03$^b$</td>
</tr>
<tr>
<td>4.4* ± 0.49</td>
<td>5.13 ± 0.68$^{ab}$</td>
<td>0.026</td>
<td>75 ± 3.3$^b$</td>
<td>61 ± 0.6$^{ab}$</td>
<td>0.093 ± 0.03$^a$</td>
</tr>
<tr>
<td>6* ± 0.50</td>
<td>4.51 ± 0.36$^{ab}$</td>
<td>0.037</td>
<td>79 ± 2.8$^b$</td>
<td>71 ± 10.4$^{ab}$</td>
<td>0.213 ± 0.04$^b$</td>
</tr>
<tr>
<td>7* ± 1.5</td>
<td>3.92 ± 0.26$^a$</td>
<td>0.027</td>
<td>53 ± 16.2$^a$</td>
<td>45 ± 7.8$^a$</td>
<td>0.085 ± 0.01$^a$</td>
</tr>
</tbody>
</table>

Leachate recirculation $^*$ of +10% and $^{**}$ 20%, $\eta$ removal efficiencies. Means with the same letter are not significantly different.

Figure 3 | UASB performance $\bullet$ OLR, $\Diamond$ $Q_{CH4}$.

Table 4 | UASB reactor performance at different organic load rate (OLR) for each SLR in the AHLB

<table>
<thead>
<tr>
<th>SLR (gVS L$^{-1}$ d$^{-1}$)</th>
<th>$L_x$ WW</th>
<th>$O_L$ gCOD L$^{-1}$ d$^{-1}$</th>
<th>$\eta_{COD}$ %</th>
<th>$Q_{CH4}$ L$^{-1}$ d$^{-1}$</th>
<th>$Y_{CH4}$ LCH4 kg VS$^{-1}$ d$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8 ± 0.70</td>
<td>13 0.92</td>
<td>6.6 ± 0.66</td>
<td>96 ± 1.4$^a$</td>
<td>2.10 ± 0.4$^a$</td>
<td>228 ± 2.6$^b$</td>
</tr>
<tr>
<td>4.4 ± 0.19</td>
<td>20 2.3</td>
<td>9 ± 1.70</td>
<td>95 ± 2.1$^a$</td>
<td>3.32 ± 0.9$^{bc}$</td>
<td>279 ± 9.4$^c$</td>
</tr>
<tr>
<td>4.4* ± 0.49</td>
<td>17 2.3</td>
<td>7 ± 1.01</td>
<td>95 ± 2$^a$</td>
<td>2.59 ± 0.3$^{ab}$</td>
<td>238 ± 13.7$^{bc}$</td>
</tr>
<tr>
<td>6* ± 0.50</td>
<td>26 2.3</td>
<td>9 ± 0.46</td>
<td>89 ± 1$^b$</td>
<td>3.16 ± 0.3$^{ab}$</td>
<td>180 ± 30$^a$</td>
</tr>
<tr>
<td>7* ± 1.5</td>
<td>19 0.92</td>
<td>13 ± 1.45</td>
<td>96 ± 1.7$^a$</td>
<td>4.42 ± 0.7$^c$</td>
<td>155 ± 15.2$^a$</td>
</tr>
</tbody>
</table>

SLR = solid load rate, $L_x$ = leachate, WW = wastewater. Means with the same letter are not significantly different.
et al. (2013) and Bo & Pin-Jing (2014), and yields above those reported by Stabnikova et al. (2008), Xu et al (2011) and Tran & Palenzuela (2012).

CONCLUSIONS

An anaerobic digestion centered process combining the treatment of municipal wastewater and organic solid wastes was assayed. A leach bed reactor was used to hydrolyze the OFMSW and the produced leachates were mixed with MWW and treated in a UASB reactor to obtain methane. The mixing degree will depend on the WWTP capacity but it can be as small as to provide a dilution sufficient to load 25 g COD L\(^{-1}\) d\(^{-1}\), as reported elsewhere (Ramirez et al. 2014).

Considering the AHLB reactor, the optimum SLR is 6 g VS L\(^{-1}\) d\(^{-1}\) based on solids destruction and COD reduction, but when combined with the UASB reactor, the best load is 4.4 g VS L\(^{-1}\) d\(^{-1}\) based on the methane to VS yield (Y\(_{\text{CH}_4} = 279 \text{ L}_{\text{CH}_4}/\text{kg VSd}\)).

As leachates are highly degradable, the UASB efficiency is 95%; this process helps in the recovery of methane from diluted wastewaters.

The proposed system is able to separate hydrolysis and acidogenesis in the first reactor, maintaining conditions that favor this phase (pH, VFA), and methanogenesis in the second reactor.

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REFERENCES


Tran, L., Palenzuela, A. & Nakasaki, K. 2012 Anaerobic digestion of organic fraction of municipal solid waste (OFMSW) in


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