Anaerobic treatability of leachate: a comparative evaluation for three different reactor systems

* TUBITAK Marmara Research Center, Gebze, Kocaeli, Turkey
** Department of Environmental Engineering, Faculty of Civil Engineering, Istanbul Technical University, 80626 Maslak, Istanbul, Turkey

Abstract  In this study landfill leachate from two young municipal landfill sites were treated in three bench-scale systems including anaerobic sequencing batch reactors (ASBR), anaerobic hybrid bed filter (AHBF) and upflow sludge blanket reactor (UASBR) at mesophilic conditions. The experimental studies have been conducted at variable influent leachate CODs of 1900–19000 mg.l⁻¹ and hydraulic retention times (HRT) of 10 to 1.5 days and solid retention times (SRT) of 40 to 10 days in ASBRs. Influent leachate concentrations and HRTs of AHBF were varied in the range of 4000 to 15000 mg.l⁻¹ and 5.1 to 0.9 days, respectively. Anaerobic treatability studies have been performed for about 20 months using 3.5 year old landfill leachate for ASBR and AHBF. The anaerobic treatability of the second leachate which was only two years old was investigated in the lab-scale UASBR for about 4 months. The influent CODs of the UASBR were varied from 9000 to 25000 mg.l⁻¹. HRTs ranged from 1.7 to 2.35 days in the same period. COD removals were in the range of 92 to 94% at the related operating conditions. The steady-state performance data of anaerobic reactors fit quite well to the linearized second-order multicomponent substrate removal kinetic model with a correlation of more than 98%.

Keywords Anaerobic treatment; biogas production; kinetic evaluation; landfill leachate

Introduction

The landfill leachate containing organic and inorganic compounds, is a complex mixture with foul odour. The most important source of the leachate is precipitation around the sanitary landfill area. The moisture content of solid wastes is also another source of leachate. The flow rate and composition of sanitary landfill leachates vary depending on the site, season and age of the landfill. Leachate from young landfills usually contains high concentrations of volatile fatty acids (VFA). These readily degradable volatile acids account for the bulk of the chemical oxygen demand (COD) of young leachate, so the ratio of biological oxygen demand (BOD) to COD is relatively high (Lema et al., 1988). As the solid waste ages, the biodegradation fraction of organic pollutant in leachate decreases, as a result of the anaerobic decomposition taking place in the landfill site (Henry et al., 1987).

Treatment of the sanitary landfill leachate by conventional and high rate anaerobic systems has been studied by many investigators (Boyle and Ham, 1974; Cameron and Koch, 1980; Bull et al., 1983; Henry et al., 1987; Kennedy et al., 1988; Wu et al., 1988; Chang, 1989; Iza et al., 1992; Keenan et al., 1992; Nedwell and Reynolds, 1996). They used young leachate (BOD/COD>0.5) and achieved variable treatment efficiencies in lab-scale treatment systems. The anaerobic pre-treatment is not satisfactory enough to discharge leachate from the young sanitary landfills to the surface waters and additional post-treatment is required (Ozturk et al., 1999b, 1999c; Kabdasli et al., 2000).

Several high-rate systems are presently available for the anaerobic treatment of landfill leachates. In this paper, a comparative evaluation has been made for three different reactor configurations, including ASBR, AHBF and UASBR to treat landfill leachate.
Materials and method

Anaerobic reactors

ASBR. Six bench-scale ASBRs used in this study were constructed from 14 cm internal diameter glass bottles. Each reactor has 18 cm height and 2 l of operating volume. The reactors were filled up to one-half of the available volume. Leachate used in this study (leachate 1) was obtained from the Harmandali Municipal Landfill site (Izmir) with an age of about 3.5 years. The characteristics of the leachate used in this study was presented in Table 1.

AHBF. AHBF was made of 11.5 cm ID of cylindrical glass. Empty bed volume was 3.35 l. Reactor consisted of two sections: 0.5 l unpacked zone at the bottom, 1/3 of which was conical, a 2.5 l filter section filled with 5/8 inch plastic ball rings with 90% porosity (specific surface area was 322 m²/m³). Total available liquid volume of the filter was 2.75 l. The feed (leachate 1) was introduced from the bottom of the conical part and the effluent left the reactor at the top through a gas-solid separation device.

UASBR. This reactor used in this study was made of plexiglass material and had an effective volume of 10.35 l. The internal diameter of the reactor was 12 cm, while total height was 130 cm. Wastewater (leachate 2) was fed to the reactor from the bottom by peristaltic pump. The characteristics of leachate 2 are given in Table 1.

All three reactors were set up in a constant temperature room to provide mesophilic conditions. More information about the ASBR, AHBF, and UASBRs can be found elsewhere (Timur and Ozturk, 1997; Ozturk et al., 1999a).

Wastewater

Leachate 1 was obtained from Harmandali Landfill site of the city of Izmir. It had been receiving municipal solid waste for 3.5 years when this study was started.

Leachate 2 supplied from Kemerburgaz Sanitary Landfill Site of Istanbul and had been receiving municipal solid waste for two years.

The composition of the raw leachate from Harmandali (leachate 1) and Kemerburgaz (leachate 2) municipal landfill sites is shown in Table 1. These data indicates that leachates were relatively stable with alkaline pH. The BOD:COD ratios of 0.5 to 0.67 were typical for a young landfill leachate.

Start-up

ASBRs and AHBF were started up with acetate and glucose enrichment culture that had been fed by feed stock for eight months. One litre feed stock contained 152 g COD (100 g

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Leachate 1 Min-max</th>
<th>Leachate 2 Min-max</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.3-7.8</td>
<td>5.6-7.0</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
<td>10,750-11,000</td>
<td>21,000-25,000</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>16,200-20,000</td>
<td>35,000-50,000</td>
</tr>
<tr>
<td>TKN-N (mg/l)</td>
<td>1,350-2,650</td>
<td>2,370</td>
</tr>
<tr>
<td>NH4-N (mg/l)</td>
<td>1,120-2,500</td>
<td>2,020</td>
</tr>
<tr>
<td>Alkalinity (mg/l)</td>
<td>7,050-12,100</td>
<td>11480-13140</td>
</tr>
<tr>
<td>Volatile acids (mg/l)</td>
<td>7,700-9,500</td>
<td>-</td>
</tr>
<tr>
<td>PO4-P (mg/l)</td>
<td>48-80</td>
<td>5-6</td>
</tr>
<tr>
<td>SO4^2- (mg/l)</td>
<td>350</td>
<td>1000</td>
</tr>
</tbody>
</table>
from acetic acid, 50 g from glucose and 2 g from leachate 1), 6 g NaHCO₃, 0.96 g N and 0.16 g P. The ASBRs were fed 100 ml d⁻¹ of feed stock to yield 10 days of hydraulic retention time and 343 mg COD l⁻¹.d⁻¹ of organic loading. 10 ml.day⁻¹ of leachate were added to the feed. Experiments were started after achieving the same COD removal rate with the same gas production rate to maintain the same activity baseline for all ASBRs. AHBF was started up by feeding diluted leachate. The organic loading rate was increased from 0.8 kg COD m⁻³.d⁻¹ to 16.5 kg COD m⁻³.d⁻¹ by decreasing HRT or increasing influent COD concentration. Since leachate 1 had appropriate amount of N and P, these nutrients were not supplemented through the experimental studies. The pH values in ASBRs and AHBF were in the range 7.4–8.0 without any pH adjustment throughout the study.

UASBR was seeded with sludge taken from a full-scale UASBR treating baker’s yeast production wastewater. Average volatile solids (VS) concentration was 10 g l⁻¹ at the beginning of the study. The reactor was started by feeding the diluted leachate with a COD of 10,000 mg.l⁻¹ at hydraulic retention time of 2.8 d. The corresponding organic loading rate (OLR) was 3.7 kg COD.m⁻³.d⁻¹. 6N H₂SO₄ solution was added to the reactor directly to maintain the pH below 8. Phosphorus was supplemented to the feed leachate (leachate 2) as phosphoric acid to provide COD:N:P ratio 350:5:1 in the system. The reactors were operated at 35±2°C during the study.

The daily measured parameters were COD, pH, biogas production rate, volatile (VSS) and total (TSS) suspended solids in the mixed reactor content and the settled effluent. The biogas was collected in a displacement graduated cylinder connected with a water reservoir for volumetric measurements at atmospheric pressure. The ASBRs were fed daily with a predetermined amount and strength of leachate during the fill period (10 minutes) and then operated in the batch treatment mode. After the reaction period (22.5 hours), the reactor mixture was allowed to settle for 70 minutes and the supernatant was withdrawn from the reactors. This took about 10 minutes. Each reactor was operated at the same cycle length (1 day). AHBF was fed with diluted leachate and then the influent COD was increased gradually.

The ASBR contents were intermittently mixed using magnetic bars and stirrers connected to the timer that was on one minute in one hour. At the end of 70 minutes settling period, withdrawn supernatant was not completely free of suspended solids. The amount of suspended solids withdrawn with the supernatant was determined daily and taken into account in daily deliberate biomass wasting to maintain the solids retention time (SRT) at a predetermined level.

Routine analyses such as pH, suspended solids, alkalinity and COD were determined according to Standard Methods (AWWA, 1995). Biogas flow-rates for UASBR were measured by wet test meter. Methane contents in the gas from the ASBR and AHBF were determined by gas chromatography (Packard 439), using an FID detector and High Sep N column.

Results and discussion
COD removal
In the ASBR studies the volumetric loading rate, \( B_v \), was increased from 0.19 to 10 g COD l⁻¹.d⁻¹ by decreasing HRT (from 10 to 1.5 days) and/or increasing influent COD concentration (from 1875 to 15400 mg l⁻¹). The sludge retention time \( \theta_x \) was kept at a predetermined value by deliberate wasting a certain amount of mixed liquor considering the VSS lost by the effluent.

In the AHBF, \( B_v \) was increased from 0.78 to 16.6 g COD l⁻¹.d⁻¹ by decreasing HRT (from 5.1 to 0.9 d) or increasing influent COD concentration (from 515 to 10260 mg.l⁻¹).

The UASBR was operated for more than 120 days. Volumetric loading rates (\( B_v \)) were varied from 3.7 to 10.7 kg COD m⁻³.d⁻¹. Table 2 summarizes steady-state averages of the
operating results from the ASBR, AHBF and UASBR systems. Bv versus COD removal efficiency (E COD) graphs is given in Figure1 for three different reactor systems. The results indicated that in the AHBF, Bv could, surprisingly, not be increased beyond 7.0 kg COD m⁻³ . d⁻¹ for COD removals of more than 60%. The authors believe that this result is not a general case and is specific for the present study. In the ASBR and UASBR, volumetric loading rates of 10 kg COD m⁻³ . d⁻¹ were applicable and corresponding COD removals were 73 and 92%, respectively.

Biogas production

ASBR and AHBF. Methane content of the biogas ranged from 47.7–74.8%. Methane conversion in all these experiments averaged 0.227 m³ CH₄ kg COD rem⁻¹ at STP. Maximum methane production rate (MPR) of 1.79 m³ CH₄ m⁻³ . d⁻¹ was achieved at maximum Bv of 10 kg COD CH₄ m⁻³ . d⁻¹ which is slightly lower than 2 m³ CH₄ m⁻³ . d⁻¹ reported for AHBF treating landfill leachate at 10 kg COD m⁻³ . d⁻¹ loading rate (Kennedy et al., 1988). At about the same values of Bv, different MPRs were evident depending on specific COD loading rate and MLVSS in the reactor. Similarly, for the same specific COD loading rates, different MPRs have been observed depending on volumetric COD loading rate and VSS concentration in the reactor.

UASBR. The relationship between the daily gas production rate (Qg) and CODs removed (Bv) were observed as illustrated in Figure 2. The average biogas production yield (Y gas) was determined as 0.44 l per g COD removed. Since the expected CO₂ content of the digester gas was less than 10% for the UASBR operating conditions (pH=8.0, alkalinity
Kinetic evaluation

The kinetic evaluation was made considering the second-order multicomponent substrate removal kinetics given by Grau et al. (1975). The following linearized form of the model was used to test the experimental data from our study.

\[
\frac{\theta}{E} = a \pm b \theta \\
(1)
\]

where: \(E\) : COD removal efficiency (%), \(\theta\) : hydraulic retention time, \(a: S_o / (k_2(s) X_o)\), \(S_o\) : influent COD, mg l\(^{-1}\), \(X_o\): reactor average VS content, mg VSS l\(^{-1}\), \(k_2(s)\): second-order substrate removal rate constant, d\(^{-1}\), \(b\): a constant greater than unity.

More information about the model can be found elsewhere (Grau et al., 1975, Ozturk et al., 1990). The experimental data from ASBR, AHBF and UASBR were applied to this model. The plot of \(\theta / E\) versus \(\theta\) gives a straight line with a correlation of 98%. The intercept of the straight line gives the value of \(a=0.203\) d, 0.013 d and the slope of \(b= 1.156\) and 1.066 for ASBR and UASBR, respectively. The AHBF data fit the ASBR data very well in this study range. The ASBR, AHBF and UASBR effluent CODs can be predicted using Eq. 2 converted from Eq. 1.

\[
\frac{\theta}{E} = 0.01 + 1.254 \theta \\
(2)
\]

The second-order rate constant calculated for ASBR was \(k_2=10.5\) d\(^{-1}\) and 38.5 d\(^{-1}\) for UASBR. Table 3 summarizes model constants \(a\), \(b\) and second-order rate constants.

Table 3 Summary of the second-order kinetic studies for anaerobic treatment

<table>
<thead>
<tr>
<th>Type of wastewater</th>
<th>Reactor type</th>
<th>Inf. COD (mg l(^{-1}))</th>
<th>HRT (d)</th>
<th>(k_2(s)) (d(^{-1}))</th>
<th>(X_o) (g VSS l(^{-1}))</th>
<th>(a) (d)</th>
<th>(b)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal wastewater</td>
<td>UASBR</td>
<td>230-445</td>
<td>0.25-1.0</td>
<td>2.17</td>
<td>7-10</td>
<td>0.02</td>
<td>1.346</td>
<td>Ubay (1994)</td>
</tr>
<tr>
<td>Olive mill effluent</td>
<td>UASBR</td>
<td>7000-23000</td>
<td>0.8-1.4</td>
<td>2.0</td>
<td>12-60</td>
<td>0.087</td>
<td>1.31</td>
<td>Ubay and Ozturk (1997)</td>
</tr>
<tr>
<td>Landfill leachate</td>
<td>UASBR</td>
<td>9000-25000</td>
<td>1.7-2.85</td>
<td>38.5</td>
<td>17.6-29.5</td>
<td>0.013</td>
<td>1.066</td>
<td>This study</td>
</tr>
<tr>
<td>Landfill leachate</td>
<td>ASBR</td>
<td>1875-15400</td>
<td>1.5-10</td>
<td>10.5</td>
<td>1.6-4.8</td>
<td>0.203</td>
<td>1.156</td>
<td>This study</td>
</tr>
<tr>
<td>Landfill leachate</td>
<td>ASBR, AHBF</td>
<td>1875-25000</td>
<td>1.5-10</td>
<td>-</td>
<td>1.6-29.5</td>
<td>0.01</td>
<td>1.254</td>
<td>This study</td>
</tr>
</tbody>
</table>

Figure 3 Evaluation of \(a\) and \(b\) constants in Eq. 1

5000 mg CaCO\(_3\) l\(^{-1}\) and T=35±1°C, the methane yields were predicted as about 0.39 l CH\(_4\) per g COD removed.

More information about the model can be found elsewhere (Grau et al., 1975, Ozturk et al., 1990). The experimental data from ASBR, AHBF and UASBR were applied to this model. The plot of \(\theta / E\) versus \(\theta\) gives a straight line with a correlation of 98%. The intercept of the straight line gives the value of \(a=0.203\) d, 0.013 d and the slope of \(b= 1.156\) and 1.066 for ASBR and UASBR, respectively. The AHBF data fit the ASBR data very well in this study range. The ASBR, AHBF and UASBR effluent CODs can be predicted using Eq. 2 converted from Eq. 1.

\[
\frac{\theta}{E} = 0.01 + 1.254 \theta \\
(2)
\]

The second-order rate constant calculated for ASBR was \(k_2=10.5\) d\(^{-1}\) and 38.5 d\(^{-1}\) for UASBR. Table 3 summarizes model constants \(a\), \(b\) and second-order rate constants.
determined in some previous studies. It should be considered that the \( k_2 \) coefficient is a function of \( \frac{S_o}{X_o} \) (i.e. F/M) and \( k_2 \) values in Table 3 are the averages of the experiments.

Conclusions

The results of the study demonstrate that anaerobic treatment is an effective and feasible option for young municipal landfill leachates. COD removals of more than 90% can be achieved by ASBR and UASBRs at organic loading rates as high as 10 kg COD m\(^{-3}\).d\(^{-1}\).

The second-order multi-component substrate removal kinetics can be applied to explain the anaerobic treatment process for the young landfill leachates. Despite anaerobic pre-treatment being a very effective treatment method for high strength leachates, additional post-treatment is needed to satisfy discharge limits. Various post-treatment alternatives including chemical (ammonia stripping, magnesium ammonium phosphate (MAP) precipitation), membrane and aerobic biological processes are possible for this purpose.

References


