Anaerobic-Fed and Sequencing-Batch Treatment of Sugar-Beet Processing Wastes: A Comparative Study

Emrah Alkaya, Göksel N. Demirer*

ABSTRACT: The aim of this study was to compare a batch-fed continuously mixed anaerobic reactor (FCMR) with an anaerobic sequencing batch reactor (ASBR), in terms of waste stabilization and methane production treating sugar-beet processing wastewater and beet-pulp simultaneously. A reactor was operated as FCMR, which then was operated as an ASBR by changing operational conditions after the steady-state was reached. Although the hydraulic retention time value of the ASBR configuration was lower (8 days) than that of the FCMR (15 days) and the corresponding organic loading rate (OLR) was higher (0.71 to 1.33 g COD/L-d), increased biomass retention enabled a significant increase in biomethanation for the ASBR configuration. So, methane production yield of 255 ± 11 mL/g COD-added was increased to 337 ± 15 mL/g COD-added (32.2% increase in methane yield) when the configuration was changed from FCMR to ASBR. The experimental results indicated that the ASBR configuration, which was applied to sugar-beet processing wastes for the first time, was superior to the FCMR configuration. Water Environ. Res., 83, 247 (2011).

KEYWORDS: anaerobic digestion, sequencing batch reactor, sugar industry, beet pulp.

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Introduction
As one of the earliest biological waste treatment methods, anaerobic digestion has evolved to be an established technology and now is being used for the treatment of a wide variety of organic wastes originating from domestic, industrial, and agricultural activities. The organic fraction of municipal solid waste (Hartmann and Ahring, 2005; Nguyen et al., 2007), domestic wastewater (van Haandel et. al., 2006), waste activated sludge (Bolzonella et al., 2005; Romano and Zhang, 2008), fruit and vegetable wastes (Bouallagui et al., 2005), animal manure (Demirer and Chen, 2004; Gungor-Demirci and Demirer, 2004; Hartmann and Ahring, 2005), sugar industry wastes (Farhadian et al., 2007; Hutnan et al., 2001; Koppar and Pullamanappalli, 2008), pharmaceutical wastewater (Oktcm et al., 2006), and brewery effluents (Connaughton et al., 2006) are among the numerous waste types that are suitable for anaerobic biological treatment. In addition to the ability of bio-product formation, anaerobic treatment has some other advantages over aerobic treatment, such as very little excess sludge production, no or little nutrient requirement, high-strength waste treatment ability, seasonal operation flexibility, and lower operational costs (Gavrilescu, 2002).

Throughout history, anaerobic digesters evolved from low-rate reactors, such as simple septic tanks and anaerobic ponds, to modern and sophisticated high-rate reactors, such as anaerobic filters and upflow anaerobic sludge blankets (van Haandel et al., 2006). Currently, there are numerous types of anaerobic reactor configurations used for the treatment of various organic wastes. One of these configurations is the anaerobic sequencing batch reactor (ASBR). In this suspended-growth process, microorganisms are allowed to contact substrate after a sufficient biodegradation period, and biomass is settled in the same vessel for solid-liquid separation and increased biomass retention. The operation of an ASBR involves four steps—(1) feed, (2) react, (3) settle, and (4) withdraw. As alternatives to continuous systems, anaerobic batch reactors have been studied extensively, as a result of their superior process control and biomass retention (Zaiat et al., 2001). Like all other reactor configurations, ASBR systems have some disadvantages also. One of the drawbacks of the ASBR system is its instability in the biogas production rate, which is considerably high immediately after the feeding step and declines with time. In addition, the need for sophisticated control systems requires special care, in terms of operation.

In this study, laboratory-scale ASBR and FCMR systems were used for the simultaneous treatment of sugar industry wastewater and beet pulp. Both systems were evaluated and compared in terms of treatment and biogas production yields. In this study, the ASBR system was investigated for the treatment of sugar-beet processing wastes for the first time, filling a gap in the literature.

Materials and Methods
Waste Characteristics. During a beet campaign period, wastewater and beet pulp were obtained from a sugar plant in Amasya, Turkey. Wastewater was settled for 1 hour, which represents primary sedimentation in treatment plants, before characterization. By means of this application, inorganic suspended materials were eliminated from the wastewater. After this application, the wastewater was frozen at −20°C before being used in the experiments. The characteristics of the wastewater are given in Table 1. Before use in the experiments, the beet pulp was dried at 105°C for 24 hours and then grinded and homogenized using a pestle. Table 2 lists the characteristics of the pressed beet pulp.

Inoculum. During startup of the experiments, mixed anaerobic sludge, obtained from the municipal wastewater treatment
The following chemicals were fed to the reactor as the basal medium, to supply the necessary nutrients for optimum anaerobic microbial growth (concentrations are given in parentheses as mg/L): NH₄Cl (1200), MgSO₄·7H₂O (400), KCl (400), Na₂S·9H₂O (300), CaCl₂·2H₂O (50), (NH₄)₂HPO₄ (80), FeCl₂·4H₂O (40), CoCl₂·6H₂O (10), KI (10), MnCl₂·4H₂O (0.5), CuCl₂·2H₂O (0.5), ZnCl₂ (0.5), AlCl₃·6H₂O (0.5), NaMoO₄·2H₂O (0.5), H₂BO₃ (0.5), NiCl₂·6H₂O (0.5), NaWO₄·2H₂O (0.5), and cysteine (10) (Gungor-Demirci and Demirer, 2004).

Analytical Methods. Standard Methods (APHA et al., 2005) were followed throughout the study for the determination of solids (total solids [TS], volatile solids [VSS], suspended solids [SSS]; total chemical oxygen demand (tCOD) (for beet-pulp characterization), total Kjeldahl nitrogen (TKN), total phosphorus (Pₜₜₒₜₜ), sludge volume index (SVI), and alkalinity. The tCOD and soluble COD (sCOD) (0.45-μm filtered) determinations were carried out by the closed reflux method. For this purpose, vials (for 0 to 1500 mg/L) were prepared for spectrophotometric determinations (SN 05827, PC Multidirect, Germany). A pH meter (HI 8314, Hanna Instruments, Italy) and electrode (HI 1230, Hanna Instruments) were used for pH measurements. Oxidation–reduction potential (ORP) values were measured using a pH meter (pH 510, Eutech, Singapore) and ORP electrode (Recorder S-500C, Sensorex, Italy).

A water-displacement device was used for the measurement of daily biogas production (Erguder et al., 2000). Biogas compositions were determined using a gas chromatograph (Thermo Electron Corporation, Waltham, Massachusetts). Hydrogen (H₂), carbon dioxide (CO₂), oxygen (O₂), methane (CH₄), and nitrogen (N₂) gases were separated in parallel connected columns (CP-Moliseve 5A and CP-Porabond Q, Varian Inc., Santa Clara, California) and detected by a thermal conductivity detector using helium (He) as a carrier gas. During the measurements, oven, inlet, and detector temperatures were set to 45, 50, and 80°C, respectively.

Volatile fatty acid (VFA) determinations also were carried out by using a gas chromatograph (Thermo Electron Corporation). Before the samples were subjected to chromatographic analyses, some pretreatments were applied. First, the samples were filtered through 0.22-μm pore-sized filters. Then, pH values of the samples were lowered to below 2.5 by using 98% formic acid to ensure the dominance of undissociated forms of VFAs.

The gas chromatograph used for VFA determinations was equipped with a Nukol column (model 25 326, 15 m × 0.53 mm, Nukol, St. Louis, Missouri). Acetic, propionic, butyric, isobutyric, valeric, iso-valeric, caproic, iso-caproic, and heptanoic acids were separated through the chromatographic analyses. Temperatures of the inlet and flame ionization detector were set to 250 and 280°C, respectively, during the analyses. The oven temperature was increased from 100 (initial) to 200°C (final) by means of 8°C/min ramping. Helium was the carrier gas with a constant flowrate of 6 mL/min.

Experimental Setup and Procedures

The reactor (glass vessel), having a 1150-mL effective volume and 50-mL headspace, was operated as an FCMR, which then was operated as an ASBR by changing the operational conditions after steady-state was reached. During both operational periods, a stock solution, containing basal medium with equal amounts of pulp and wastewater, in terms of COD, was fed daily to the reactor as influent. Characteristics of influent are given in Table 3.

Table 1—Wastewater characteristics (settled for 1 hour).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tCOD</td>
<td>6621 ± 113.2</td>
</tr>
<tr>
<td>sCOD</td>
<td>6165 ± 517.1</td>
</tr>
<tr>
<td>Total solids</td>
<td>6062 ± 53.0</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>2832 ± 25</td>
</tr>
<tr>
<td>TSS</td>
<td>665 ± 21.2</td>
</tr>
<tr>
<td>VSS</td>
<td>335 ± 7.1</td>
</tr>
<tr>
<td>pH</td>
<td>6.62</td>
</tr>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>1760</td>
</tr>
<tr>
<td>TKN</td>
<td>10</td>
</tr>
<tr>
<td>P_total</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 2—Pressed beet-pulp characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>85 ± 0.1</td>
</tr>
<tr>
<td>Total solids (%)</td>
<td>15 ± 0.1</td>
</tr>
<tr>
<td>Volatile solids %TS</td>
<td>94 ± 0.01</td>
</tr>
<tr>
<td>COD (g/g dry weight)</td>
<td>1.22 ± 0.15</td>
</tr>
<tr>
<td>TKN (%)TS</td>
<td>7.28</td>
</tr>
<tr>
<td>P_total (%)TS</td>
<td>1.0 ± 0.28</td>
</tr>
</tbody>
</table>

Table 3—Influent characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tCOD</td>
<td>10 600</td>
</tr>
<tr>
<td>sCOD</td>
<td>5318 ± 288</td>
</tr>
<tr>
<td>Total solids</td>
<td>9193</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>6348</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>4832</td>
</tr>
<tr>
<td>VSS</td>
<td>4268</td>
</tr>
<tr>
<td>tVFA (as H-Ac)</td>
<td>892 ± 16</td>
</tr>
<tr>
<td>pH</td>
<td>7.65</td>
</tr>
</tbody>
</table>

The gas chromatograph used for VFA determinations was equipped with a Nukol column (model 25 326, 15 m × 0.53 mm, Nukol, St. Louis, Missouri). Acetic, propionic, butyric, iso-butyric, valeric, iso-valeric, caproic, iso-caproic, and heptanoic acids were separated through the chromatographic analyses. Temperatures of the inlet and flame ionization detector were set to 250 and 280°C, respectively, during the analyses. The oven temperature was increased from 100 (initial) to 200°C (final) by means of 8°C/min ramping. Helium was the carrier gas with a constant flowrate of 6 mL/min.
of the effluent (L/d). 

The daily wasted volume of the mixed liquor (L/d), represented the waste sludge characteristics. As a consequence of the periodical waste of sludge, the SRT was kept between 24 and 30 days. When this information was combined with the data obtained from the values of other operational parameters (biogas production, pH, alkalinity, solids, and VFA concentrations), it was postulated that steady-state was achieved in 40 days. This time period is in agreement with the theoretical time of 3×HRT needed for reaching steady-state conditions. At steady-state conditions, the influent tCOD concentration of 10 600 mg/L was decreased to 3322 ± 235 mg/L as effluent, which correspond to a 68.7 ± 2.2% tCOD removal. On the other hand, the sCOD concentration was determined as 484 ± 40 mg/L. This value was achieved after an initial increase, with a peak value of 1804 mg/L (at day 10), followed by a subsequent decrease. A pronounced increase in the sCOD concentration was a direct result of VFA accumulation (Figure 4d).

Because biomass separation was not practiced, mixed liquor of the reactor represents the effluent solids concentrations also (Figure 4b). After 40 days of operation, total and volatile solids concentrations were recorded as 6504 ± 379 mg/L, respectively, at steady-state. When the influent concentration of volatile solids (6348 mg/L) was taken into consideration, 54.7% reduction was computed. Figure 4b also shows that the mixed-liquor suspended solids (MLSS) and the tCOD concentrations of the reactor were stabilized at 3322 ± 235 mg/L, after a decreasing period of 35 to 40 days. When this information was combined with the data obtained from the values of other operational parameters (biogas production, pH, alkalinity, solids, and VFA concentrations), it was postulated that steady-state was achieved in 40 days. This time period is in agreement with the theoretical time of 3×HRT needed for reaching steady-state conditions. At steady-state conditions, the influent tCOD concentration of 10 600 mg/L was decreased to 3322 ± 235 mg/L as effluent, which correspond to a 68.7 ± 2.2% tCOD removal. On the other hand, the sCOD concentration was determined as 484 ± 40 mg/L. This value was achieved after an initial increase, with a peak value of 1804 mg/L (at day 10), followed by a subsequent decrease. A pronounced increase in the sCOD concentration was a direct result of VFA accumulation (Figure 4d).

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Because biomass separation was not practiced, mixed liquor of the reactor represents the effluent solids concentrations also (Figure 4b). After 40 days of operation, total and volatile solids concentrations were recorded as 6504 ± 197 mg/L and 2878 ± 379 mg/L, respectively, at steady-state. When the influent concentration of volatile solids (6348 mg/L) was taken into consideration, 54.7% reduction was computed. Figure 4b also shows that the mixed-liquor suspended solids (MLSS) and
MLVSS concentrations were stabilized at 2847 ± 194 mg/L and 1980 ± 173 mg/L, respectively.

During the early days of operation (0 to 20 days), VFAs (acetic, propionic, and iso-butyric acids) were accumulated in the system (Figure 4d). At their peak concentration values, acetic, propionic, and butyric acids were measured as 475, 649, and 48 mg/L, respectively. It was an expected result, because the highest concentrations of VFAs typically are observed in the form of acetic, propionic, butyric, and iso-butyric acids during the startup of anaerobic systems (Rittmann and McCarty, 2001). It is thought that the main reason for this situation was higher growth rates of acidogenic microorganisms compared with methanogens. It took time (10 to 30 days) for methanogens to mature in the system and start converting VFAs into methane. As a result, acetic, propionic, and iso-butyric acids were diminished to below 50 mg/L after 30 days of operation, a level that was sustained until the end of operation.

Biogas composition of the reactor was analyzed frequently, and the steady-state values were recorded. A remarkable observation was the considerably high methane percentages in biogas (81.9 ± 4.7%) when compared with typical values of 65 to 70% (Gerardi, 2003). This was because of the calcium ion (Ca\(^{2+}\)), which commonly is found in sugar-beet processing wastewaters because of the use of lime (Iza et al., 1990). In sugar-beet factories, lime is added to flume/wash water to adjust its pH and improve the settling characteristics. As expected, the wastewater used in this study included considerable amounts of Ca\(^{2+}\) (378 mg/L) (Table 1). It is known that lime reacts with soluble carbon dioxide to form bicarbonate alkalinity [Ca(HCO\(_3\))\(_2\)] and precipitates (CaCO\(_3\)) (eqs 3 and 4). This is supported by Gerardi (2003), who claimed that the carbon dioxide in biogas can replace the amount lost in the sludge as a result of the discussed reactions. This situation explains the lower carbon dioxide (18.1 ± 1.3%) and relatively higher methane percentages (81.9 ± 4.7%) in biogas.

Figure 3—Temporal variations of control parameters of reactors: (a) HRT-SRT, (b) biogas production, (c) pH, and (d) alkalinity.

Figure 4—Temporal variations of control parameters of reactors: (a) COD, (b) mixed-liquor solids (for the FCMR system, the mixed liquor also represents the effluent), (c) effluent solids, and (d) VFA.
Steady-state daily methane production was used to calculate the methane production yield, which was determined as 255 ± 11 mL/g COD-added. This methane yield was higher than the yield (210 mL/g COD-added) calculated by Weiland (1993), who obtained the result during conventional anaerobic digestion of beet pulp alone. This difference can be associated directly with the addition of wastewater that has readily biodegradable organics (soluble carbohydrates) when compared with beet pulp. Another reason for this difference might be the addition of basal medium in (soluble carbohydrates) when compared with beet pulp. Another reason for this difference might be the addition of basal medium in

\[
\text{Ca(OH)}_2 + 2\text{CO}_2 \rightarrow \text{Ca(HCO}_3)_2
\]  
\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]  

Chemical Oxygen Demand Balance for Batch-Fed Continuously Mixed Anaerobic Reactor System. A COD balance calculation was carried out, including methane production (as COD removal), to evaluate the COD removal data, calculated by the influent and effluent COD concentrations (eqs 5, 6, and 7). All parameters were calculated by using steady-state values. On a daily basis, input-COD (0.795 g) was compared with output-COD (methane-COD as 0.514 ± 0.035 g + effluent COD as 0.249 ± 0.018 g), which was computed as 0.763 ± 0.039 g. This result indicates that input-COD and output-COD were nearly equal. The coefficient of variation of 2.9% (from input to output) indicated that the data were sufficiently reliable. Consequently, the percentage of COD removal, calculated by methane production (64.6 ± 2.8%), matches the percentage calculated by influent and effluent COD concentrations (68.7 ± 2.2%). This double-check also indicates the reliability of the experimental results in terms of total COD removal.

\[
\text{Input-COD (g/d)} = \text{Output-COD (g/d)}
\]  
\[
\text{COD}_i = \text{COD}_e + \text{COD}_m
\]  
\[
\frac{Q \times C_i}{\text{COD}_i} = \left(\frac{Q \times C_e}{\text{COD}_e}\right) + \left(\frac{Q_m \times T_m}{\text{COD}_m}\right)
\]  

Where

\[
\text{COD}_i = \text{influent COD (g/d)},
\]
\[
\text{COD}_e = \text{effluent COD (g/d)},
\]
\[
\text{COD}_m = \text{COD equivalent of daily produced methane (g/d)},
\]
\[
Q = \text{daily waste-feed volume (L/d)},
\]
\[
Q_m = \text{daily methane production (L/d)},
\]
\[
C_i = \text{influent COD concentration (g/L)},
\]
\[
C_e = \text{effluent COD concentration (g/L)},
\]
\[
T_m = \text{theoretical COD equivalence of methane at 35°C and 1 atm (2.53 g/L methane)}
\] (Speece, 1996).

Anaerobic Sequencing Batch Reactor. When the operational scheme of the reactor was shifted to the sequencing-batch mode (ASBR), a quick response was noticed in daily biogas productions (Figure 3b). Following an increase for 5 to 7 days, a steady production was reached. At steady-state, daily biogas production was averaged to give 648 ± 10 mL/d. This significant rise in biogas production, when compared with FCMR data, was a result of higher biomass retention, in addition to the increase in OLR value, from 0.71 to 1.33 g COD/L·d. During the change from the FCMR to ASBR system, a slight decrease was observed in pH values (Figure 3c), which can be associated with the slight increase in VFA concentrations (Figure 4d). Meanwhile, the alkalinity value was maintained between 2700 and 2800 mg/L as CaCO₃ (Figure 3d). It can be postulated that the optimum conditions for an efficient anaerobic digestion process were sustained in terms of pH and alkalinity values.

One piece of evidence of increased biomass retention in the ASBR configuration was the increasing tCOD concentrations of the mixed liquor (Figure 4a). Before it reached a steady-state value of 7785 ± 239 mg/L, the tCOD concentration was increased for 30 days. On the other hand, the tCOD concentration of the effluent (supernatant, remained after settling) was maintained between 1329 and 952 mg/L, with the steady-state value of 1008 ± 38 mg/L. The notable difference between tCOD-reactor (mixed-liquor) and tCOD-effluent indicates the remarkable settling performance of biosolids. When enhanced biomethanation was assisted with biomass separation via gravity settling, an influent tCOD concentration of 10 600 mg/L decreased to 1008 ± 38 mg/L—a difference of 90.5 ± 3.6%. In addition, by COD balance calculations, the tCOD removal was computed as 79.7 ± 1.1%, taking into account the daily wasted sludge-COD (eqs 8, 9, and 10). On the other hand, the sCOD was sustained at 503 ± 10 mg/L at a steady-state condition.

Figure 4b shows that the mixed-liquor solids concentrations (total solids, volatile solids, MLSS, and MLVSS) showed an increasing trend, which began with the startup of the ASBR operation. The observed increase in solids concentration, which lasted for 25 to 30 days, provided evidence of increased biomass retention. Particularly, the MLVS concentrations were crucial, representing biomass retention. At steady-state conditions, the MLVSS concentration was detected as high as 4470 ± 222 mg/L. Unlike in the case of the mixed liquor, effluent solids concentrations did not deviate from the startup until the end of operation (Figure 4b). By using MLVSS (mixed liquor) and VSS (effluent), the SRT was determined periodically, as described in the Experimental Setup and Procedures section. Manipulation of the SRT value through sludge wasting is a common practice for ASBR operations (Cheong and Hansen, 2008; Timur and Öztürk, 1999). In this study, by means of deliberate wasting of sludge, the SRT was stabilized at 29.1 ± 0.2 days as a steady-state value (Figure 3a).

The VFA concentrations were increased slightly (from 10–30 mg/L to 20–70 mg/L) after changing the reactor configuration from FCMR to ASBR. Ghosh (1987) states that, in an anaerobic treatment system, an increase in the OLR value typically causes VFA accumulation and a corresponding pH decrease. In this study, accumulation of VFAs was insignificant (20 to 70 mg/L), although the OLR value was increased almost 2-fold (from 0.71 to 1.33 g COD/L·d). This situation occurred because of the prolonged retention of methanogenic microorganisms in the system. At an SRT value of 29.1 ± 0.2 days, methanogens were able to enrich in the system and effectively convert produced VFAs into methane.

Chemical Oxygen Demand Balance for Anaerobic Sequencing Batch Reactor System. As it was the case for the FCMR system, COD balance calculations were carried out for the ASBR configuration, to express the tCOD removal performance and associate it with methane production (eqs 8, 9, and 10). The results
show that 1.53 g of daily COD input was removed from the reactor as methane (1.31 ± 0.06 g COD/d), waste-sludge (0.19 ± 0.01 g COD/d), and effluent of the reactor (0.12 ± 0.00 g COD/d) at steady-state conditions. Thus, 1.53 g COD/d input was close to the value of the output, which was 1.62 ± 0.06 g COD/d. The coefficient of variation of 4.0% (from input to output) indicates the high reliability of the gathered data. Thus, iCOD removal, calculated by methane production (85.6 ± 3.9%), was slightly higher than the removal percent (79.7 ± 1.1%) calculated by the COD concentrations of waste-sludge and effluent.

\[
\text{Input mass of COD (g/d)} = \text{Output mass of COD (g/d)}
\]

\[
\frac{\text{COD}_i}{\text{COD}} = \frac{\text{COD}_e + \text{COD}_w + \text{COD}_m}{\text{COD}}
\]

\[
\frac{Q_i \times C_i}{\text{COD}} = \frac{(Q_i \times C_e) + (Q_w \times C_w) + (Q_m \times T_m)}{\text{COD}}
\]

Where

COD\_i = influent COD (g/d),
COD\_e = effluent COD (g/d),
COD\_w = waste-sludge COD (g/d),
COD\_m = COD equivalent of daily produced methane (g/d),
Q\_i = daily feed volume (L/day),
C\_i = influent COD concentration (g/L),
Q\_e = daily effluent volume (L/day),
C\_e = effluent COD concentration (g/L),
Q\_w = daily waste-sludge volume (L/day),
C\_w = daily waste-sludge COD concentration (g/L),
Q\_m = daily methane production (L/day), and
T\_m = theoretical COD equivalence of methane at 35°C and 1 atm (2.53 g COD/L methane) (Speece, 1996).

**Methane Production Rate in Anaerobic Sequencing Batch Reactor System.** One of the major characteristics of the ASBR system is the high initial food concentration (F/M), a driving force for metabolic activity, which results in an increased substrate utilization rate immediately after feeding (Dague et al., 1992). The substrate utilization rate (in other words, the methane production rate) is of paramount importance, because it determines the extent of COD removal and settling characteristics of sludge at the end of a cycle. Figure 5 depicts the methane production over time for the ASBR system at the reaction step during a steady-state condition. Because the F/M ratio was decreased with time, the methane production rate, the major barrier for the settling of sludge, decreased also. This situation favors biomass settling and sludge retention, at the end of the reaction step of the ASBR system (Dague et al., 1998).

The methane production rate of the reactor was modeled using a first-order rate equation (eq 11). The regression analysis indicated that the experimental results were in good agreement with the modeled function \((R^2 = 0.9830)\), with 95% confidence limits. Ultimate methane production \((G_f)\) was computed as 540.2 ± 8.8 mL, while \(k\) was determined as 0.196 ± 0.012 hour\(^{-1}\) (Table 4). On the other hand, the experimentally found total methane production rate was very close to the computed \(G_f\) value. This result indicated that the methane production rate was lowered at the end of the cycle, which was a suitable condition for efficient biomass settling.

\[
G_t = G_t (1 - e^{-kt})
\]

Where

\(G_t\) = cumulative methane generation at time \(t\) (mL),
\(G_f\) = ultimate methane generation (mL),
\(k\) = first-order rate constant (day\(^{-1}\)), and
\(t\) = time (days).

**Sludge Settling Characteristics of the Anaerobic Sequencing Batch Reactor System.** In the operating cycle of an ASBR system, the sludge settling step is critical, because it determines the effluent characteristics and enables biomass retention. Indeed, there are numerous studies in the literature regarding the improvements in biomass settling in the ASBR configuration, including biomass granulation (Wirtz and Dague, 1997; Zaiat et al., 2001). As Dague et al. (1992) stated, low substrate concentrations and resulting low methane production, achieved at the end of the reaction step, create ideal conditions for biomass flocculation and separation.

The SVI assay is used widely to determine the settleability of treatment sludge. Sludge with an SVI less than 100 mL/g is regarded as very well-settled sludge, while a value, greater than 100 mL/g indicates settling problems (Vesilind, 1980). In this study, SVI experiments were carried out to inspect sludge settling throughout the 45 days of operation of the ASBR. The results indicated that sludge was highly settleable (SVI of 57.4 ± 4.9 mL/g) from the beginning of the operation until the end (Figure 6). Vesilind (1980) stated that sludge settling was adversely affected by the increase in sludge concentration. In this study, fluctuation of the SVI value was insignificant, although the
MLSS concentration was increased from 2847 ± 194 mg/L to a steady-state value of 6450 ± 257 mg/L. This information supported the idea that the settling characteristics of produced sludge were desirable for an effective biomass separation.

In fact, sugar industry wastewater is well-known for the ability to produce highly settleable sludge when using the anaerobic contact process, which relies on biomass sedimentation and recycle (Hobson and Wheatley, 1993). This high settleability is mainly because of the inherent Ca\(^{2+}\) content of the wastewater caused by lime addition as a coagulant during beet processing. The effect of calcium concentrations on bioflocculation and granulation in anaerobic digestion was studied by some researchers (Langerak et al., 1998; Yu et al., 2001). Yu et al. (2001) advocated that calcium concentrations from 150 to 300 mg/L enhance the biomass accumulation and granulation during the startup of an upflow anaerobic sludge bed (UASB) reactor. This explains the reason behind the determined high settleability, when the Ca\(^{2+}\) concentration of used wastewater (378 ± 5.7 mg/L) was taken into consideration. Metal cations present in basal medium also could stimulate the coagulation process, which needs to be further investigated.

**Comparison of the Treatment Efficiencies for Batch-Fed Continuously Mixed Anaerobic Reactor and Anaerobic Sequencing Batch Reactor Systems.** Although the influents were the same, there was a remarkable difference between the effluents of the FCMR and ASBR systems (Table 5). This difference was a direct result of the enhanced biomethanation, followed by efficient sludge sedimentation in the ASBR configuration. As depicted in Figure 3a, SRT values were determined as 15 days and 29.1 ± 0.2 days, respectively, for the FCMR and ASBR systems. Although the HRT value of the ASBR configuration was lower (8 days) than that of FCMR (15 days), the corresponding OLR was higher (from 0.71 to 1.33 g COD/L-d), as discussed, the biomass retention enabled a significant increase in biomethanation for the ASBR. Thus, the methane production yield of 255 ± 11 mL/g COD-added was increased to 337 ± 15 mL/g COD-added (32.2% increase in methane yield) when the configuration was changed to the ASBR (Table 5). In addition, the tCOD removal was increased from 68.7 ± 2.2% to 79.7 ± 1.1%. Volatile solids reduction in the ASBR system was computed as 70.0 ± 1.3%, while this value remained as 54.7 ± 6.0% in the FCMR configuration. This difference corresponds to an increase in volatile solids reduction of approximately 22.0 ± 0.1%.

Although the ASBR was proven to be an efficient system for the treatment of various wastes, such as swine manure (Droste and Masse, 1995), landfill leachate (Timur and Öztürk, 1999), dairy manure (Dugba and Zhang, 1999), coking wastewater (Li et al., 2005), and brewery wastewater (Xiangwen et al., 2008), it was applied to sugar-beet processing wastes for the first time. The experimental results indicate that, in terms of treatment performances, the ASBR system was competitive with other reactor configurations that are used for anaerobic digestion of beet-pulp (Table 6).

**Conclusions**

In this study, sugar-beet processing wastes (wastewater and beet-pulp) were subjected to anaerobic microbial degradation in two different reactor configurations—FCMR and ASBR. The results of the experiments were analyzed and reported in a comparative fashion for both of the reactor configurations.

Although the HRT value of the ASBR configuration was lower (8 days) than that of FCMR (15 days), the ASBR achieved a higher specific methane yield (337 ± 15 mL/g COD-added) than FCMR (255 ± 11 mL/g COD-added). Moreover, tCOD removal was higher in the ASBR (68.7 ± 2.2%) than in the FCMR (79.7 ± 1.1%). The readily degradable COD was converted to methane relatively quickly, in approximately 8 hours (see Figure 4) in the ASBR and most likely in the FCMR also. Therefore, it may be stated that the ASBR achieved a higher specific methane yield because the SRT was increased from 15 to 29 days in the ASBR. The higher specific methane yield of the ASBR may be the result of a higher fraction of influent VSS conversion to methane and more endogenous decay of biomass. The experimental results indicated that the ASBR system is a viable reactor configuration for the anaerobic digestion of beet-pulp.

**Credits**

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**Table 5**—Influent and effluent concentrations at steady-state.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (mg/L)</th>
<th>FCMR effluent* (mg/L)</th>
<th>ASBR effluent (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tCOD</td>
<td>10600</td>
<td>3322 ± 235</td>
<td>1008 ± 38</td>
</tr>
<tr>
<td>sCOD</td>
<td>5318 ± 288</td>
<td>484 ± 40</td>
<td>503 ± 10</td>
</tr>
<tr>
<td>Total solids</td>
<td>9193</td>
<td>6504 ± 197</td>
<td>4286 ± 79</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>6348</td>
<td>2878 ± 379</td>
<td>1238 ± 101</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>4832</td>
<td>2847 ± 194</td>
<td>637 ± 15</td>
</tr>
<tr>
<td>VSS</td>
<td>4268</td>
<td>1980 ± 173</td>
<td>578 ± 26</td>
</tr>
<tr>
<td>tVFA (as H-Ac)</td>
<td>892 ± 16</td>
<td>10 to 30</td>
<td>20 to 70</td>
</tr>
<tr>
<td>pH</td>
<td>7.65</td>
<td>7.25</td>
<td>7.20</td>
</tr>
</tbody>
</table>

* In the FCMR system, effluent represents the mixed liquor, because biomass separation was not practiced.
Table 6—Comparison of the anaerobic treatment systems, adapted from Koppar and Pullammanappallil (2007).

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>HRT (days)</th>
<th>OLR (g COD/L·d)</th>
<th>Methane yield (mL g VS added)</th>
<th>VS reduction (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSTR</td>
<td>27 ± 8</td>
<td>5.7 ± 1.7</td>
<td>0.358</td>
<td>81 ± 2</td>
<td>Frostell et al. (1984)</td>
</tr>
<tr>
<td>CSTR</td>
<td>2.4 to 7</td>
<td>0.9 to 2.7</td>
<td>0.346 to 0.355</td>
<td>NA</td>
<td>Stoppok and Bucholz (1985)</td>
</tr>
<tr>
<td>Non-stirred tank</td>
<td>1 to 17</td>
<td>2.5 to 6.7</td>
<td>0.352</td>
<td>NA</td>
<td>Hutnan et al. (2000)</td>
</tr>
<tr>
<td>CSTR-UASB</td>
<td>13</td>
<td>2</td>
<td>0.235</td>
<td>92</td>
<td>Hutnan et al. (2001)</td>
</tr>
<tr>
<td>Leach-bed</td>
<td>7</td>
<td>4</td>
<td>0.336b</td>
<td>96</td>
<td>Koppar and Pullammanappallil (2008)</td>
</tr>
<tr>
<td>FCMR</td>
<td>15</td>
<td>0.71</td>
<td>0.426 ± 0.018</td>
<td>54.7 ± 6.0</td>
<td>Present study</td>
</tr>
<tr>
<td>ASBR</td>
<td>8</td>
<td>1.33</td>
<td>0.563 ± 0.025</td>
<td>70.0 ± 1.3</td>
<td>Present study</td>
</tr>
</tbody>
</table>

\* NA = not available.  
\* Reported at standard temperature and pressure.

References


