Enhancing Dairy Lagoon Performance with High-Rate Anaerobic Digesters

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G. L. Hawkins, D. R. Raman, R. T. Burns, R. E. Yoder, T. L. Cross

ABSTRACT: In a two-stage study, the possibility of using high-rate anaerobic digesters to enhance the performance of dairy lagoons was explored. Four anaerobic sequencing batch reactors (ASBR) and four downflow anaerobic filters (DAF) were tested, with two of each type operated at 25 °C, and the other two at 35 °C. The first stage of the experiment explored using the high-rate digesters on liquid effluent from a screw-press treating dairy manure slurry. The first-stage experiment demonstrated that settling processes, rather than biodegradation, accounted for most of the organic matter reduction in both reactor types, when operated at a 0.5–d hydraulic retention time. Specifically, settling accounted for an average of 100% of the chemical oxygen demand (COD) removal in the ASBR reactors, and for an average of 72% of the COD removal in the DAF reactors. These results prompted the second stage of the experiment, which explored the possibility of using the reactors to remove volatile fatty acids (VFAs) from dairy lagoon supernatant. Diluted manure slurry was spiked with acetic acid (HAc) to simulate the supernatant of an overloaded lagoon. At VFA loading rates of 1.0 and 3.0 kg HAc m⁻³ d⁻¹, both reactor types achieved moderate VFA removal. However, at a loading rate of 6.0 kg HAc m⁻³ d⁻¹, the ASBR reactors were ineffective, whereas the DAF reactors, at both 25 °C and 35 °C, removed more than 80% of the influent HAc. At a loading rate of 12 kg HAc m⁻³ d⁻¹, the DAFs achieved removal rates of 75%; removal rates dropped to 50% at the maximum loading tested, 24 kg HAc m⁻³ d⁻¹. Based on these experiments, it appears that the DAF reactors are suited to the task of rapidly removing accumulated VFA from lagoon supernatant.

Keywords. ASBR, Anaerobic sequencing batch reactor, Anaerobic filter, Odor control, VFA, Dairy waste.

Anaerobic lagoons are used for storage and treatment of waste and wastewater from industrial, municipal, and agricultural sources, with treatment occurring through settling and microbial breakdown and stabilization of organic matter in the waste. If operated in accordance with recommended organic loading rates, stabilization of the waste materials proceeds with minimal odors (ASAE Standards, 1999; USDA–SCS, 1992). However, if the organic loading rate increases, the rapid conversion of complex compounds to intermediate fatty acids (e.g., acetic, propionic, butyric) can lower the lagoon pH. This lower pH can in turn suppress the methanogenic population, thereby causing incomplete degradation of the waste, increased lagoon odors, and intensified odors during land application of the lagoon contents (Powers and Van Horn, 1998; Powers et al., 1999). In addition to odor problems, land application of unstable waste may contaminate surface waters and groundwater through the leaching and runoff of excess organic matter (Arceivala, 1981; Hobbs et al., 1995).

Assuming a constant inflow rate of wastewater, a reduction in lagoon organic loading rate can be achieved through two distinct means: by increasing the lagoon volume or by lowering the concentration of organic matter in the influent. At some agricultural production operations, the former option may not be viable due to either economics or available land area. Based on Hernandez and Rodriguez (1992), Hawkins and Raman (1999) hypothesized that lowering the concentration of organic material entering the lagoon might be accomplished through use of a high-rate anaerobic digestion (HRAD) system. Preliminary calculations suggested that enhancing lagoon function with a high-rate bioreactor might be economically feasible and practical, since the storage function of the lagoon would be maintained, and since the high-rate bioreactor would only function to maintain lagoon organic loading rates within prescribed limits. This article reports the results of experiments conducted to explore the possibility of enhancing lagoon function with HRAD systems, in two distinct configurations.

Experiments were conducted on large, lab-scale reactors (25-L working volume) operated at ambient (~25°C) and mesophilic (35°C) temperatures. Based on a report by Hernandez and Rodriguez (1992), the initial goal was to explore the potential for these reactors to remove approximately half the organic matter, measured as chemical oxygen demand (COD), in the waste when operated at retention times...
of less than 1 d. Preliminary calculations suggested that such a reactor, placed between a solids separator and a lagoon (fig. 1, configuration A) might be a cost–effective remedy for overloaded lagoons. However, this goal proved unreachable; the reactors achieved low organic removal rates and low methane productivity when operated at the short retention times considered necessary for economic viability of this approach. A second approach was then tried, wherein the potential of removing accumulated volatile fatty acids (VFAs) from dairy wastewater lagoons was explored. In this approach, the lagoon serves as a settling basin, and the reactor only receives lagoon supernatant (fig. 1, configuration B).

This article presents results from dairy wastewater treatment experiments conducted with two types of high–rate anaerobic digestion systems, the anaerobic sequencing batch reactor, or ASBR (Sung and Dague, 1992), and the downflow anaerobic filter, or DFAF (Wilkie and Colleran, 1989). The objectives of the experiments were to: (1) determine if solids settling in the two reactor types contributed significantly to removal of organic matter from the wastewater, and (2) compare the VFA removal rates for the ASBR and DFAF reactor types operating on identical dairy wastewater streams.

MATERIALS AND METHODS

REACTOR COMPONENTS

Eight reactors were built and operated as described in Table 1. All had a working volume of 25 L (DFAF vessels had a total volume of 40 L to allow for 15 L of packing media) and were constructed of 25–cm (10 in.) dia. schedule 40 PVC pipe. Liquid levels were maintained at 82 cm and 51 cm above the reactor bottom in the DFAF and ASBR, respectively. All four ASBR reactors were housed adjacent to one another, in one bank of reactors, and the DFAF reactors were housed similarly in a second bank of reactors. Each bank of reactors was monitored and controlled by a separate datalogger (Model 23X, Campbell Scientific, Logan, Utah).

Each DFAF included ports for influent, effluent, sampling, and sludge wasting (fig. 2). Two ports in the cap of each reactor allowed biogas collection and temperature probe insertion, while a port in the reactor bottom allowed sludge wasting. The influent port was located 7.5 cm above the liquid level to enhance wastewater distribution across the media. A sampling port was located approximately halfway between the influent and effluent ports. The effluent port was located 2.5 cm above the reactor bottom.

The DFAF packing media consisted of lava rock (Mountain West – Colorado Aggregate Company, Alamosa, Colo.), composed primarily of aluminum, calcium, iron, magnesium, and sodium silicates (Colorado Aggregate Company, 1988). This material has a surface area to volume ratio similar to that of plastic media (ca. 250 m² m⁻³), is low cost (ca. 25 to 100 times cheaper than plastic media on a surface–area basis), and has a relatively low bulk density (600 kg m⁻³) (Hawkins, 2000).

Each ASBR was also constructed with ports for influent, effluent, sampling, and sludge wasting (fig. 3). The cap of each reactor contained ports for the influent, biogas collection, temperature probe insertion, and sludge depth sampling. Four ports along the side of each reactor allowed precise control of the decanting level, and thereby the volume decanted per draining event.

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Table 1. Guide to reactors, showing reactor number, reactor type (ASBR = anaerobic sequencing batch reactor, DFAF = down–flow anaerobic filter), and operating temperature.

<table>
<thead>
<tr>
<th>Reactor number</th>
<th>Reactor type</th>
<th>Operating temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>ASBR</td>
<td>25</td>
</tr>
<tr>
<td>R2</td>
<td>ASBR</td>
<td>35</td>
</tr>
<tr>
<td>R3</td>
<td>ASBR</td>
<td>25</td>
</tr>
<tr>
<td>R4</td>
<td>ASBR</td>
<td>35</td>
</tr>
<tr>
<td>R5</td>
<td>DFAF</td>
<td>25</td>
</tr>
<tr>
<td>R6</td>
<td>DFAF</td>
<td>35</td>
</tr>
<tr>
<td>R7</td>
<td>DFAF</td>
<td>25</td>
</tr>
<tr>
<td>R8</td>
<td>DFAF</td>
<td>35</td>
</tr>
</tbody>
</table>

---

Figure 1. Two approaches for enhancing lagoon system performance using a high–rate anaerobic digester (HRAD) operating at a short hydraulic retention time (HRT). Configuration A shows the initial approach, in which the HRAD treats solid–separated wastewater prior to lagoon treatment. Configuration B shows the final approach, in which the lagoon functions as a hydrolysis reactor and solids separator, and lagoon supernatant is pumped through the HRAD for rapid removal of volatile fatty acids.

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Figure 2. Schematic representation of downflow anaerobic filter (DFAF). Not to scale.
Reactor temperatures were monitored with type–T thermocouples. Optically isolated relays (Model OAC5, Opto22, Temecula, Cal.) enabled datalogger control of reactor temperature, via 120–V, 50–W heating pads, surrounded by fiberglass insulation to minimize heat loss. Gas production from each reactor was monitored with submerged tipping buckets equipped with reed switches to enable electronic tip counting (Hawkins, 2000). The tipping buckets were calibrated to 30 mL tip⁻¹, allowing measurement of biogas production.

Dairy wastewater ([COD] > 70 g L⁻¹) was collected from the liquid effluent side of a Vincent screw press (Model KP–6 w/2.3–mm screen, Vincent Corp., Tampa, Fla.) located at the Tennessee Agricultural Experiment Station Dairy near Lewisburg, Tennessee. This concentrated material was diluted to an approximate COD concentration of 5 g L⁻¹. Initially, this dilution was performed to facilitate reactor start–up; the intention was to increase the influent concentration significantly as the reactors came on line. During the VFA removal experiments, the dilute manure solution was spiked with acetic acid to simulate the supernatant in an overloaded lagoon with an offensive odor (du Toit, 1987).

Separate multi–channel peristaltic pumps (Model 5773–80, Cole Palmer, Chicago, Ill.) were used to feed each bank of four reactors. All pumps were controlled with optically isolated relays (OAC5 or 120D10, Opto22, Temecula, Cal.) connected to the dataloggers. The DAF reactors were fed hourly, with the liquid level in the reactor being controlled by the elevation of a standpipe and the hydraulic retention time (HRT) being controlled through the volume of liquid introduced to the reactor.

The ASBR reactors were batch loaded every 6 h. The ASBR reacts phase was 4 h, with mixing occurring for 5 min every h; the ASBR settling phase lasted 2 h. Reactor filling occurred just prior to the react phase, and decanting took place immediately after the settling phase. A submersible pump (Model 1–42, Little Giant Pump Co., Oklahoma City, Ok.) on each ASBR was used for effluent discharge and a separate pump (Model 1P372, Little Giant Pump Co.) mixed the reactor contents. The mixing pumps were sized to provide vigorous agitation (0.4 – 0.6 kW m⁻³) of the reactor contents (Geankoplis, 1993). The HRT of an ASBR depends on the total fill–settle–react–decant time, as well as on the volume decanted. Since the time of each operation was held constant, HRT in the ASBRs was controlled through the selection of the decanting port height (which determined the volume removed on each decant cycle).

Influent and effluent wastewater samples were collected and analyzed for COD and VFA thrice weekly during the solids accumulation test and daily during the VFA removal experiment. Influent COD samples were collected at the inlet of the influent pumps. Chemical oxygen demand was measured using a closed reflux micro method (method #8000, HACH Company, Loveland, Colo.). Volatile fatty acid concentrations were analyzed on an HP 6890 series gas chromatograph using a crosslinked polyethylene glycol column, and are reported in units of mg L⁻¹ as acetic acid (HAc). Alkalinity and pH within each reactor were monitored to assess the reactor performance but are not reported here. Alkalinity and pH measurements were performed in accordance with Standard Methods for Examination of Water and Wastewater (APHA, 1998). Statistical analysis of the data was performed using SAS PROC MIXED (SAS, 1999).

### Sludge Accumulation Experiment

The following COD mass balance equation facilitated the sludge accumulation experiment:

\[
M_{\text{inf}} = M_{\text{eff}} + M_s + M_{\text{CH}_4} + M_{\text{bf}} + M_{\text{aun}}
\]

where

\[
M_{\text{inf}} = \text{mass added by the influent}
\]

\[
M_{\text{eff}} = \text{mass lost through the effluent}
\]

\[
M_s = \text{mass collected during reactor flushing}
\]

\[
M_{\text{CH}_4} = \text{estimated mass converted to methane}
\]

\[
M_{\text{bf}} = \text{mass from the backflush and draining operation (DAF reactors only)}
\]

\[
M_{\text{aun}} = \text{mass unaccounted for.}
\]

A one–month experiment was conducted to determine values of the terms in equation 1 for each reactor. At the start of the experiment, the ASBR reactors were drained and their sludge volume was set to 10 L; the DAF reactors were drained and refilled thrice with fresh wastewater to remove accumulated solids. The COD concentration of the sludge in the ASBR reactors was measured to account for initial COD mass within those reactors. The reactors were then operated at a 0.5–d HRT for one month. During this time, influent and
effluent volumes and COD concentrations were monitored daily to allow computation of $M_{of}$ and $M_{of}$, and gas production from each reactor was recorded to enable estimation of $M_{CH4}$. (The $M_{CH4}$ values were calculated assuming that 0.35 L of methane is produced per gram of COD destroyed, and that the biogas composition was 75% methane.) After one month, each reactor was drained, and the volume and COD concentration of the drained liquid from each reactor was measured to allow computation of $M_{f}$. The DFAF reactors were also backflushed and drained twice to effectively remove all accumulated solids; the volumes and COD concentrations of each backflush and drain were measured to allow computation of $M_{of}$.

**VOCALITY FATTY ACIDS REMOVAL EXPERIMENT**

The results of the sludge accumulation experiment strongly suggested that negligible biodegradation was occurring at the 0.5–d HRT. Although other researchers have shown that longer retention time reactors can treat dairy waste (Viraraghavan and Kikkeri, 1990; Monroy et al., 1994; Dugba and Zhang, 1999), the project goal remained exploring the viability of short retention time reactors for reducing and preventing VFA accumulation in overloaded lagoons. Therefore, the decision was made to explore the performance of the reactors to remove VFA from VFA–enriched dairy wastewaters, such as might occur in overloaded lagoons. In this model (diagrammed in fig. 1, configuration B), the high–rate anaerobic digesters treat supernatant from the lagoon rather than the screened raw wastewater. In so doing, the lagoon serves as a settling tank and as a hydrolysis and fermentation reactor, while the primary function of the high–rate digester is to support a large methanogenic population capable of converting VFAs to biogas.

Figure 4. Average chemical oxygen demand (COD) concentration of influent (feed) and effluent for the sludge accumulation test.

**RESULTS AND DISCUSSION**

**SLUDGE ACCUMULATION EXPERIMENT**

The working volume of the ASBR reactors remained at 25 L due to the absence of any fill material. However, during the first six months of operation, the working volumes of the DFAF reactors dropped significantly due to biomass growth on the packing material. This growth was quantified by measuring the refill volume after flushing: the working volumes of reactors 5, 7, and 8 had dropped from 25 to 15 L, and reactor 6 had dropped to 11.5 L.

The average COD concentrations of the influent and effluent during the sludge accumulation experiment are presented in figure 4. The average influent concentration of the wastewater was 5.2 g L$^{-1}$ ($\pm$0.9 g L$^{-1}$), yielding $M_{of}$ of 2160 g for all eight reactors. While a statistically significant removal of COD occurred in all reactors, the treatment efficiencies were low (ca. 25% to 39%). Reactor 1 (R1) had slightly better performance than did any of the other reactors, but no other statistically significant performance differences were noted between reactors. The COD concentrations of the sludge after the one–month sludge accumulation test are presented in figure 5, with the feed COD indicated for purposes of comparison only. Reactor sludge concentrations were greatly enriched (ca. 5.8× to 10×) compared to the feed, suggesting that significant solid settling had occurred.

The gas collection system for the ASBR reactors malfunctioned during the experiment, thus no gas data were collected for these reactors. However, previous experience suggested that the biogas production in the ASBR reactors was negligible; it is therefore reported as zero in table 2. In the DFAF reactors, $M_{CH4}$ values were greater at 35°C than at 25°C, probably reflecting greater hydrolysis and subsequent fermentation and methanogenesis at the higher temperature.

The results of the sludge accumulation experiment are summarized in table 2. Overall, the mass balance appeared tight, with less than 7% of the mass unaccounted for in any reactor (table 2, $M_{inl}/M_{inf}$ column). Settling accounted for 76% to 121% of the mass removal in the ASBR reactors, with no apparent correlation between reactor temperature and settled mass. It is counterintuitive for the settled mass to exceed the mass removed from the wastewater, but there are...
VFA REMOVAL EXPERIMENT

The VFA treatment efficiencies during the steady–state period for each reactor and feed concentration are presented in figure 6. All reactors achieved statistically significant VFA removal at influent VFA concentrations of 0.5 and 1.5 g HAc L–1 (P < 0.0001). However, at an influent concentration of 3.0 g HAc L–1, R1 did not achieve significant VFA reduction (P = 0.084), while the other ASBR reactors achieved only slightly significant treatment (P < 0.025). The low removal observed in R1 at all concentrations could not be explained.

At an influent VFA concentration of 0.5 g HAc L–1, VFA reduction was slightly greater (though not to a statistically significant degree) in the ASBR reactors than in the DFAF reactors. Under these conditions, all reactors except R1 and R7 achieved VFA removals greater than 50%. However, there was no statistically significant difference in the effluent concentrations between reactor types at 25°C (P = 0.65) or at 35°C (P = 0.34).

At an influent VFA concentration of 1.5 g HAc L–1, VFA treatment efficiency in all the ASBR reactors dropped below 51%. This decrease suggested that the ASBR reactors were reaching their maximum removal potential. The DFAF reactors at the same 1.5 g HAc L–1 feed concentration achieved greater than 65% removal, except R7, which achieved 45%. Interestingly, three DFAF reactors achieved greater VFA treatment efficiencies at the increased loading rate, perhaps reflecting recruitment of more organisms in the reactor. Reactor type significantly affected treatment efficiency at this VFA concentration, with DFAF reactors outperforming the ASBR systems at both 25°C (P = 0.017) and 35°C (P < 0.0001).

At 3.0 g HAc L–1, no ASBR reactors attained treatment efficiencies greater than 20%. In contrast, DFAF reactors, with the exception of R7, had treatment efficiencies greater than 80%. As with the 1.5 g HAc L–1 feedstock, there was a highly statistically significant difference in performance between reactor types at both at 25°C and 35°C (P < 0.0001).

With treatment efficiencies of greater than 80% for the DFAF reactors, the HRT was dropped to 0.25 d and 0.125 d while maintaining the VFA concentration at 3.0 g HAc L–1. Figure 7 summarizes the results, with the leftmost bar in each set being a reproduction of the rightmost bar from the DFAF data in figure 6. At a loading of 12 kg HAc m–3 d–1 (i.e., 3.0 g HAc L–1 at 0.25 d) R5, R6, and R8 had treatment efficiencies greater than 75%, while R7 fell to slightly below 57%. A comparison of the replicates showed a significant difference between the 25°C reactors (R5 and R7) (P < 0.0001), but no significant difference was seen between the 35°C reactors (R6 and R8) (P = 0.52). The difference between R5 and R7 is significant; however, when the replicate averages are compared across temperatures, there is no significant difference (P < 0.0001).

Table 2. Results from the sludge accumulation test. Minf = chemical oxygen demand (COD) added by the influent, Meff = mass lost through the effluent, Mch4 = mass collected during reactor flushing, MCH4 = estimated mass converted to methane, Msf = mass from the backflush and draining of the DFAF reactors only, and Mua = mass unaccounted for. Rightmost column indicates the ratio of COD settled to COD removed; the uncertainty in the rightmost column was estimated as ±16%.

<table>
<thead>
<tr>
<th>Reactor Number, type, and operating temperature (°C)</th>
<th>Minf (g)</th>
<th>Meff (g)</th>
<th>Mch4 (g)</th>
<th>MCH4 (g)</th>
<th>Msf (g)</th>
<th>Mua (Minf – Meff) (%)</th>
<th>Muf/(Minf – Meff) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ASBR 25</td>
<td>2160</td>
<td>1310</td>
<td>787</td>
<td>0.0</td>
<td>0.0</td>
<td>2.8</td>
<td>93</td>
</tr>
<tr>
<td>2 ASBR 35</td>
<td>2160</td>
<td>1570</td>
<td>448</td>
<td>0.0</td>
<td>0.0</td>
<td>6.7</td>
<td>76</td>
</tr>
<tr>
<td>3 ASBR 25</td>
<td>2160</td>
<td>1640</td>
<td>629</td>
<td>0.0</td>
<td>0.0</td>
<td>-5.0</td>
<td>121[4]</td>
</tr>
<tr>
<td>4 ASBR 35</td>
<td>2160</td>
<td>1530</td>
<td>691</td>
<td>0.0</td>
<td>0.0</td>
<td>-2.9</td>
<td>110[4]</td>
</tr>
<tr>
<td>5 DFAF 25</td>
<td>2160</td>
<td>1560</td>
<td>519</td>
<td>72.8</td>
<td>62.5</td>
<td>-2.8</td>
<td>87</td>
</tr>
<tr>
<td>6 DFAF 25</td>
<td>2160</td>
<td>1580</td>
<td>335</td>
<td>135.0</td>
<td>57.1</td>
<td>2.5</td>
<td>58</td>
</tr>
<tr>
<td>7 DFAF 25</td>
<td>2160</td>
<td>1540</td>
<td>549</td>
<td>33.0</td>
<td>55.6</td>
<td>-0.9</td>
<td>89</td>
</tr>
<tr>
<td>8 DFAF 25</td>
<td>2160</td>
<td>1540</td>
<td>347</td>
<td>97.4</td>
<td>58.4</td>
<td>5.5</td>
<td>56</td>
</tr>
</tbody>
</table>

[a] Values above 100% are not physically reasonable and are due to measurement errors.

Two factors that could account for this: error in the measurement of Meff, or significant temporal variations in influent and effluent COD concentration. The former appears more likely, since the particulate nature of the ASBR sludge made accurate COD measurements challenging.

A propagation of error calculation, based on estimated uncertainties in the raw volume and COD concentration measurements, suggested that an uncertainty of ±16% would be likely in the Muf/(Minf – Mch4) values. (Significant temporal variations in COD concentration appear a less likely source of error, since the low values of Muf/Minf suggest that the mass balance was generally accurate.) Settling accounted for 56% to 89% of the mass removal in the DFAF reactors, with reactor temperature significantly affecting the fraction of COD settled. Specifically, settling accounted for 88% of the removal in the 25°C reactors, but only 57% of the removal in the 35°C reactors. The greater MCH4 values and lower solids accumulations in the 35°C DFAF reactors strongly support the hypothesis that hydrolysis limited the degradation of dairy wastewater at the 0.5–d HRT.
At the highest VFA loading rate of 24 kg HAc m⁻³ d⁻¹ (i.e., 3.0 g HAc L⁻¹ at 0.125 d) the VFA treatment efficiencies ranged from 31% to 52%. At this loading rate, a comparison of the reactors at the two temperatures shows a significant difference (P < 0.0001) between the effluent VFA concentrations. Likewise, there is a significant difference between the replicate reactors (P < 0.0007 for both temperatures).

A plot of the VFA loading rate and VFA removal rate data collected from the VFA experiment is shown in figure 8. The data was fit to a hyperbolic parabola (e.g., Monod or Michaelis–Menten equation) with r² values of 0.85 and 0.90 for the 25°C and 35°C data, respectively. The maximum VFA removal rates predicted by the curve were 15 kg HAc m⁻³ d⁻¹ at 25°C and 20 kg HAc m⁻³ d⁻¹ at 35°C. The half saturation constants were likewise determined to be 16.5 and 18.5 kg HAc m⁻³ d⁻¹ for 25°C and 35°C, respectively.

The 70% VFA treatment efficiency observed in DFAF reactors receiving VFA loadings of 12.0 kg HAc m⁻³ d⁻¹ translates into a volumetric VFA removal rate of 8.4 kg HAc m⁻³ d⁻¹. To put this number into perspective, it can be compared to the recommended maximum volatile solids (VS) loading rates for lagoons in Tennessee, which ASAE gives as 0.072 kg VS m⁻³ d⁻¹ (ASAE Standards, 1999). Since the VS to COD ratio for dairy wastes is close to unity, the recommended lagoon loading rate can be expressed as 0.072 kg COD m⁻³ d⁻¹. One unit of acetic acid exerts 1.07 units of COD. Therefore, the volumetric COD removal rate in the DFAF reactors can be estimated as 9.0 kg m⁻³ d⁻¹, or 125× the suggested loading rate for a lagoon in Tennessee.

To achieve VFA removal rates of 125× that of a lagoon, the VFA concentration entering the DFAF must be rather high (3 g HAc L⁻¹), implying that the lagoon supernatant would have this VFA concentration. While the DFAF could conceivably be employed to “rescue” an overloaded lagoon that had reached such high VFA concentrations, one would not intentionally design a system to operate in this range, since such a high VFA concentration in the lagoon would produce highly offensive odors. Instead, to avoid significant odor problems, a lagoon/DFAF system might be expected to operate at VFA concentrations of 0.3 g HAc L⁻¹ (du Toit, 1987). In this case, a DFAF operating at a 0.125 d HRT would receive VFA at 2.4 kg HAc m⁻³ d⁻¹. Under these conditions, the data presented in figure 8 suggest that a removal rate of 1.7 kg HAc m⁻³ d⁻¹ would be achievable. Comparing this rate to the published lagoon removal rates (Safley and Westerman, 1992) suggests that the DFAF could remove VFA at 25× that achieved by anaerobic lagoons in Tennessee.

**Comparison of ASBR and DFAF Reactors**

A comparison of the reactors at a loading of 1 kg HAc m⁻³ d⁻¹ shows no significant difference (P = 0.534 at 25°C, and P = 0.336 at 35°C). Likewise, there is no difference between the reactors when operated at 3 kg HAc m⁻³ d⁻¹ at either temperature (P = 0.0001). As the loading increased to 6 kg HAc m⁻³ d⁻¹, it became apparent that the ASBR reactors had reached a point that they could not effectively treat the wastewater; however, treatment efficiency of the DFAF reactors continued to increase. As expected, there was a difference between the two reactor types at both temperatures (P = 0.0001). This large difference in the treatment efficiencies for the two reactors presents good evidence that the DFAF reactor is better suited for removal of VFAs at these higher loading rates.

On the surface, the twenty–five–fold performance difference between a DFAF and a lagoon would appear to support the feasibility of the approach proposed herein. However, there are large differences between the volumetric costs of lagoons (simple earthen structures) and DFAF reactors (typically more complex concrete or steel structures). Furthermore, this experiment was conducted with the use of a synthetic lagoon supernatant. An economic analysis based on the reactor performance presented here should be conducted. If the approach appears economically feasible, then the next experiment should involve pilot–scale testing using actual lagoon supernatant.

**Conclusion**

The removal of organic matter in anaerobic sequencing batch reactors (ASBR) and downflow anaerobic filter (DFAF) reactors operating at 0.5–d hydraulic retention time was shown to occur mainly through solids settling in the reactors. The chemical oxygen demand (COD) mass balance on the ASBR reactors showed settling could account for all of the COD removal observed. In contrast, settling accounted for 55% to 88% of the observed COD removal in the DFAF.
reactors. Furthermore, the differences between the accumulated COD in the 25°C and 35°C DFAF reactors supported the idea that hydrolysis limits the biodegradation of dairy wastewater at very short retention times.

At low loading rates (<3.0 kg HAc m⁻³ d⁻¹), both the ASBR and DFAF reactors achieved moderate volatile fatty acid (VFA) removal. At a loading rate of 6.0 kg HAc m⁻³ d⁻¹, the ASBR reactors were ineffective, while the DFAF reactors efficiently removed more than 80% of the applied acetic acid. As loading rates increased to 24 kg HAc m⁻³ d⁻¹, the treatment efficiency of the DFAFs dropped off gradually to 50%. Based on these experiments, the DFAF reactors appear well suited to the task of rapidly removing accumulated VFA from overloaded lagoons. A thorough economic analysis is needed to determine the feasibility of such an endeavor.

ACKNOWLEDGEMENTS


REFERENCES


