OPERATION AND PERFORMANCE OF A FARM-SCALE ANAEROBIC SEQUENCING BATCH REACTOR TREATING DILUTE SWINE MANURE

D. W. Hamilton, M. T. Steele

ABSTRACT. *A 400 m^3 anaerobic sequencing batch reactor (ASBR) treating dilute (0.30% to 1.0% total solids) swine manure produced by a 120-sow farrow-to-finish farm was monitored for one calendar year. The digester was operated at full reactor volume (20-day hydraulic retention time, HRT) and at conditions considered optimal for biogas production (5-day HRT). Reactor temperature during 20-day HRT operation ranged between 22°C and 32°C, and solids retention time (SRT) averaged 51 days. During 5-day HRT operation, reactor temperature was 22°C to 24°C and SRT averaged 26 days. Organic matter removal efficiency, measured as the difference between daily mass of chemical oxygen demand (COD) entering the reactor and COD leaving with decanted liquids, was 73% during 20-day HRT operation and 57% during 5-day HRT operation. Methane yield was 0.55 m^3 CH_4 kg^{-1} volatile solids (VS) during 20-day HRT and 0.38 m^3 CH_4 kg^{-1} VS during 5-day operation. In general, organic matter removal was lower and methane yield was higher than results using similar manure in laboratory-scale reactors. Volumetric reactor efficiency (VRE) was 0.18 m^3 CH_4 m^{-3} reactor d^{-1} under both operating conditions. Flushed manure was diluted 30:70 with recycled aerobic lagoon effluent to provide sufficient volume to achieve 5-day HRT operation. The VRE of an ASBR treating flushed manure without lagoon effluent dilution at 5-day HRT was estimated to be greater than 0.70 m^3 CH_4 m^{-3} reactor d^{-1} based on microbial kinetic models.*

Keywords. *Anaerobic digestion, Anaerobic sequencing batch reactor, ASBR, Efficiency, Hydraulic retention time, Methane, Methane yield, Operation, Organic matter, Solids retention time, Swine manure, Treatment.*

Adoption of anaerobic digestion technology on swine farms has lagged behind other livestock sectors. Barriers to adoption include an unfavorable economic climate, housing practices that produce highly diluted manure, poor knowledge of anaerobic digestion by swine farmers, and lack of available technology (Kramer and Bilek, 2013). The most common form of digester on hog farms, particularly farms that use flushing systems to remove manure from buildings, is a covered anaerobic lagoon (USEPA, 2014). The two drawbacks of using covered lagoons as digesters are the footprint of the lagoon, which is much larger than a mechanical digester, and the decrease in biogas production during the winter in temperate climates. If anaerobic digestion is to be adopted by the swine industry, development of high-rate digestion systems to handle dilute manure is essential.

An anaerobic sequencing batch reactor (ASBR) is a high-rate digestion system ideally suited to treat swine manure (Sung and Dague, 1995; Zhang et al., 1997). An ASBR operates in a single reactor vessel. The reactor cycles through four phases of operation: fill, react, settle, and decant. Because solids are retained during the settling phase, hydraulic retention time (HRT) can be controlled separately from solids retention time (SRT). An operator controls SRT by adjusting the mass of mixed liquor suspended solids (MLSS) removed from the reactor with wasted sludge. A short HRT reduces the size and construction cost of the digester. Hydraulic retention time of an ASBR can be set as short as needed to convert soluble organic matter to biogas, while simultaneously maintaining a longer SRT to avoid washout of methanogens.

Methane yield, the volume of methane produced per mass of organic matter loaded, achieved by laboratory-scale ASBR digesters is generally higher than that of continuously stirred reactors. Hansen et al. (1999) observed a 52% increase in biogas production when solids were settled in an intermittently stirred reactor prior to liquid decanting. Wang et al. (2009) found that ASBR digesters produced 15% to 30% more biogas than identically loaded continuously stirred reactors, and concluded that the increase in gas production was because settled solids were digested and not simply stored. Angenent et al. (2002) observed 5 L ASBR laboratory digesters treating swine manure with 2% total solids (TS). The digesters were operated at 25°C and inoculated with sludge dredged from an active swine lagoon. Methane yield remained constant at 0.46 m^3 CH_4 kg^{-1} volatile solids (VS)

Submitted for review in January 2014 as manuscript number SE 10590; approved for publication by the Structures & Environment Division of ASABE in August 2014.

The authors are **Douglas W. Hamilton, ASABE Member,** Associate Professor, Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma, and **Matthew T. Steele,** Assistant Professor, Department of Engineering and Physics, Abilene Christian University, Abilene, Texas. **Corresponding author:** Douglas Hamilton, 226 Agriculture Hall, Stillwater, OK 74078; phone: 405-744-7089; e-mail: dhamilt@okstate.edu.

Vol. 57(5): 1473-1482   © 2014 American Society of Agricultural and Biological Engineers   ISSN 2151-0032   DOI 10.13031/trans.57.10590

($R^2 = 0.9857$) over a wide range of operating conditions, i.e., organic loading rate (OLR) ranging from 0.5 to 4.0 kg VS m^{-3} d^{-1} and HRT ranging from 5 to 40 days. Zhang et al. (1997), using 12 L reactors operated at 25°C and swine manure with solids concentrations ranging between 6% and 17% TS, found that both HRT and OLR had a profound effect on methane yield. Methane yield at 3 days HRT averaged 0.23 m^3 CH_4 kg^{-1} VS regardless of OLR. At 6 days HRT, methane yield was 0.60 m^3 CH_4 kg^{-1} VS at OLR of 0.80 kg VS m^{-3} d^{-1} and 0.25 m^3 CH_4 kg^{-1} VS VS m^{-3} d^{-1} and 0.25 L CH_4 g^{-1} VS at OLR of 3.7 kg VS m^{-3} d^{-1}.

Ndegwa et al. (2005, 2008) conducted preliminary optimization studies on 18 L reactors to determine the optimum operating conditions for ASBR digesters treating low-strength (0.30% to 0.40% TS) swine manure. This range of solids concentration is consistent with manure removed by flushing and pull-plug systems. The reactors were operated at two temperatures: 20°C and 35°C. Optimum HRT for biogas production, measured as methane yield, was determined to be between 5.0 and 6.0 days. Methane yield (MY) at 6.0 days HRT (OLR of 0.60 kg VS m^{-3} d^{-1}) and 35°C was 0.19 m^3 CH_4 kg^{-1} VS, whereas MY at 6.0 days HRT and 20°C was 0.175 m^3 CH_4 kg^{-1} VS. The fact that methane yield declined only 8% at the lower temperature demonstrates that reactors with long SRT are less sensitive to operating temperature than digesters with short SRT. This stems from the fact that the specific growth rate of methanogens is highly dependent on temperature (Hashimoto, 1983). Retaining solids, and therefore cells, for longer periods than the regeneration time of methanogens reduces the chance of washout from the digester.

Ndegwa et al. (2005) found that operating an ASBR at 20°C also had a positive effect on the ability of the digester to reduce organic matter loading on downstream components. Organic matter removal efficiency (OMRE), which was measured as the percent difference between influent and effluent COD, occurred at a slightly longer HRT and cooler operating temperatures than was optimal for biogas production. The highest OMRE achieved was 90% at 7 days HRT and 20°C. The OMRE at 35°C and 7 days HRT was 84%. The authors concluded that, although conversion of organic matter to biogas declined by 8% between 35°C and 20°C, this reduction was counterbalanced by better settling and greater solids retention at the lower temperature.

Despite their superior performance with flushed swine manure, no ASBR digesters are currently operating on commercial swine farms. The lack of ASBR technology on swine farms is partially explained by the unfavorable economics of digestion in general and the lack of performance data at the farm scale (Kramer and Bilek, 2013). Two demonstration projects of farm-scale ASBR digesters were initiated in the late 1990s and 2000s. The first project, the Crawford Farm, was built on a 2800-head swine finisher unit in Nevada, Iowa. The Crawford digester was abandoned after numerous mechanical and structural problems, some of which were related to a lightning strike (Kramer, 2002, 2004). The second demonstration was initiated in 2008 on the Swine Research and Education Center at Oklahoma State University and is the subject of this article.

OBJECTIVES

- Determine the performance parameters (organic matter reduction efficiency, methane yield, and volumetric reactor efficiency) of a farm-scale ASBR operating at run-of-the-farm conditions and at the optimum hydraulic retention time for biogas production (5 days).
- Compare the organic matter reduction efficiency and methane yield achieved by the farm-scale ASBR to those observed in the laboratory by Ndegwa et al. (2005).

MATERIALS AND METHODS

A farm-scale (400 m^3) ASBR digester was constructed at the Oklahoma State University Swine Research and Education Center (OSU SREC) in Stillwater, Oklahoma (36° N, 97° W). The main purpose of the ASBR was to provide organic matter reduction for odor control. The performance goal was to achieve an OMRE of 85% based on influent and decant COD due to both organic matter destruction and settling.

MANURE HANDLING SYSTEM

The farm-scale ASBR is one component of an integrated manure handling system located at OSU SREC. The general layout is shown in figure 1. Detailed specifications can be found in Hamilton et al. (2010). The farm is essentially a 120-sow farrow-to-finish operation. During the time of this study, the total population ranged from 800 to 1200 animals. Swine are housed in 12 modular buildings. Manure is stored in pull-plug pits modified with scrapers. The pits are filled with effluent from the second, aerobic cell of a two-stage, anaerobic/aerobic lagoon. There are 21 pits on the farm with varying volumes. Manure flows to splitter box 1, where it is directed to either the two-stage lagoon or the ASBR system.

ASBR SYSTEM

The ASBR and auxiliary systems are shown in figure 2. Manure flows from splitter box 1 into lift station 1 and is pumped by a submersible chopper pump (P1 in fig. 2) into

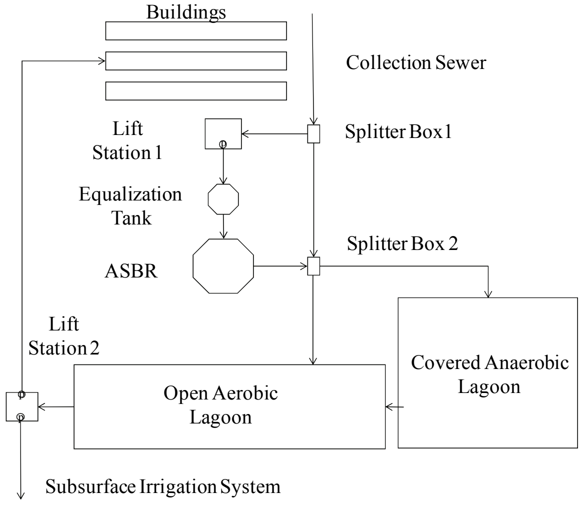

Figure 1. Schematic of OSU SREC manure handling system.

a 167 m^3 stainless steel equalization tank. The equalization tank allows the ASBR to be fed at any time of day and any day of the week regardless of the pit emptying schedule. The storage capacity of the equalization tank is 8 days.

The ASBR itself is a cylindrical (3.97 m tall with 12.2 m diameter), uninsulated, aboveground concrete tank. It is covered by an unsupported flexible membrane constructed of 30 mil XR-5 8130 material manufactured by the Seaman Corporation (Wooster, Ohio). The cover is bolted to the top of the concrete tank. An external, emergency overflow standpipe maintains the maximum reactor height at 3.75 m. The maximum ASBR volume at this height is 430 m^3. The emergency overflow standpipe houses an ultrasonic sensor (EchoSonic II, model LU27-O1, Flowline, Inc., Los Alamitos, Cal.) used by the ASBR control system (PanelView 550 PLC, Allen-Bradley, Milwaukee, Wisc.) to open and close the decant flow valve (V4 in fig. 2). The ASBR has three internal withdrawal standpipes with elevations of 3.20, 2.59, and 1.98 m. Choice of a decanting standpipe is made by manually opening or closing valves at the end of each of the three internal standpipes.

The digester was designed to treat the entire daily wastewater volume produced by pulling pits twice per week. This would result in a daily manure load of 40 m^3 with 0.5% TS. With this daily volume, HRT of the ASBR would range between 5.6 and 11 days. However, during the time of this study, the farm crew could only manually pull pits on a once-per-week schedule; therefore, the flushed manure volume was approximately 20 m^3 d^{-1} with 1.0% TS. In addition, the unsupported membrane cover made it hazardous to operate at a decant heights below 2.60 m. Gas pressure was the only support the membrane received other than floating atop the reactor liquid, and the natural sag of the membrane reached down to 2.60 m. If a rainfall event occurred during a period of low gas pressure, the unsupported membrane could tear. For this reason, the minimum allowable liquid height was set at 2.61 m. Adding feeding height gives a minimum react phase liquid height of 2.70 m. At this height, and a 20 m^3 d^{-1} manure volume, HRT is 16 days. In order to operate at an HRT of less than 16 days, effluent from the second lagoon cell was added to lift station 1 to augment the flushed manure and increase the influent volume.

The equalization tank is mixed and the ASBR is fed, heated, and mixed using various arrangements of pumps 2, 3, and 4 and automatic control valves 1, 2, and 3, shown in figure 2. Pumps 2 and 4 are 1.2 kW centrifugal pumps (B5423, Fairbanks-Morse, Kansas City, Kans.) capable of 248 m^3 h^{-1} flow at 12.9 m head. Pump 3 is a recessed-impeller centrifugal pump (Torus R2(7), Hayward Gordon, Halton Hills, Ontario, Canada) that delivers 34.2 m^3 h^{-1} flow at 12.9 m head. The sludge removal pump (P5 in fig. 2) is identical to pump 3. With pump 2 running and valve 1 closed, only the equalization tank is mixed. The ASBR alone is mixed by closing valves 1 and 2, opening valve 3, and running pump 4. When pumps 2 and 4 are running and valves 1 and 3 are open, both the equalization tank and the ASBR are mixed, and the ASBR is fed by allowing material to flow through valve 1.

Opening valve 2 and running pump 3 sends mixed liquor through a boiler/heat exchanger (HeatX ED, Walker Process Equipment, Aurora, Ill.) (HE in fig. 2). Reactor temperature was maintained above 20°C from November to March by operating the boiler. This was the only temperature control used on the ASBR. When the boiler was not in operation, reactor temperature followed ambient temperature. The upper temperature was not controlled. The ASBR could warm to as high as 32°C in summer.

The equalization tank and ASBR are mixed using jet mixer nozzles located on the floor of each tank. The heat exchanger return flow mixed the digester during the react phase with a mixing intensity of 0.028 kW m^{-3} and one volume turnover every 12 h. Pump 4 was activated to completely mix the reactor during feeding and when mixed liquor samples were taken (mixing intensity = 14. kW m^{-3}, 1.4 h per turnover).

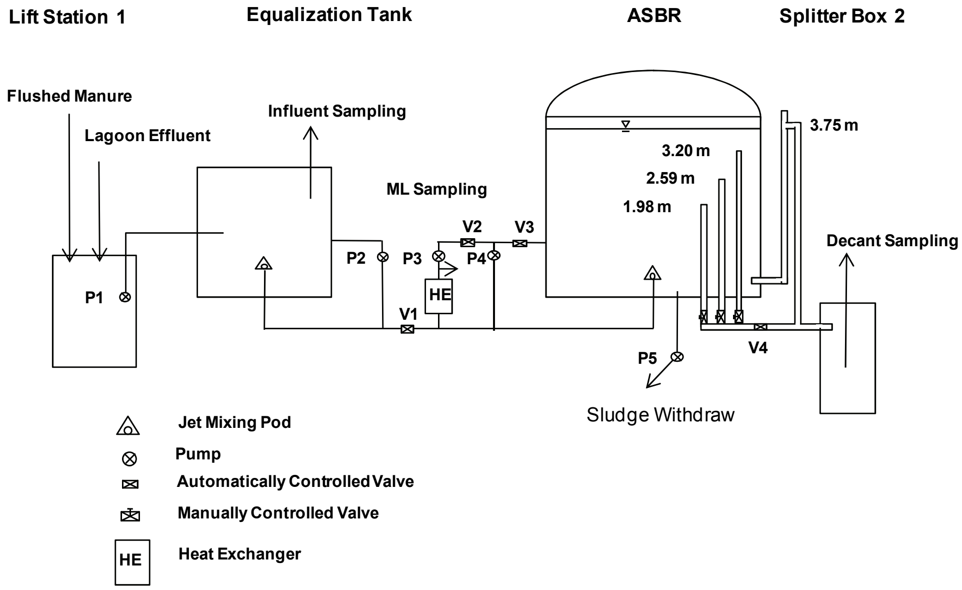

Figure 2. Schematic of ASBR and auxiliary systems.

LIQUID SAMPLING AND ANALYSIS

ASBR influent samples were taken from the equalization tank using a 0.76 L coliwasa "sludge judge" type sampler (Wheaton Science, Millville, N.J.). A column of liquid representing the entire depth of the tank was captured by the coliwasa sampler. When only flushed manure entered lift station 1, equalization tank samples also served as flushed manure samples. During times that lagoon effluent was added to the lift station, the coliwasa sampler was used to remove manure samples from splitter box 1. Samples of lagoon effluent added to lift station 1 were taken as grab samples at the hose discharge into the lift station. Grab samples of ASBR decant were taken from the pipe entering splitter box 2. Grab samples of ASBR mixed liquor were taken from a spigot located upstream of the heat exchanger.

Samples were analyzed for pH using an Accumet pH electrode (Fisher Scientific, Waltham, Mass.). Total solids (TS), total volatile solids (TVS), total fixed solids (TFS), total suspended solids (TSS), and volatile suspended solids (VSS) were analyzed according to Standard Methods (APHA, 1998). Chemical oxygen demand (COD) was analyzed using dichromate digestion vials (CHEMetrics, Midland, Va.) and analyzed colormetrically on a spectrophotometer (APHA, 1998).

BIOGAS MONITORING

Biogas production was measured using a rotary displacement meter (15C175 Roots meter, Dresser, Inc., Houston, Tex.) placed downstream of a condensation trap. A blower located after the meter provided the necessary flow and pressure for biogas flaring.

Methane production was also estimated using a mass balance of organic matter across the ASBR. Organic matter entering the reactor must equal organic matter exiting the reactor. Organic matter enters the reactor as influent (manure and lagoon effluent) and leaves the reactor as decanted liquids, sludge, and biogas. The mass balance for organic matter contained in biogas was solved using equation 1:

$$BG = MN + LE - DT - SL - \Delta R \tag{1}$$

where

BG = mass of organic matter contained in biogas

MN = mass of organic matter added from manure

LE = mass of organic matter added from lagoon effluent

DT = mass of organic matter leaving in decanted liquid

SL = mass of organic matter leaving as sludge

ΔR = change in reactor organic matter mass.

Calculating the mass of organic matter entering and leaving in the liquid and sludge streams is fairly simple. It is the volume entering or exiting multiplied by the concentration of organic matter in the stream. Sludge was not wasted every day; however, the mass of organic matter leaving as sludge (SL) can be expressed on a daily basis by dividing the mass leaving during wasting events by the number of days between events. The daily mass of organic matter accumulating in the reactor was estimated by observing the long-term trend in mixed liquor organic matter mass and then dividing this mass by the days between the start and end points of the trend.

Once the mass of organic matter leaving as biogas was established using equation 1, it was converted to a volume. Consider that most of the energy produced in anaerobic digestion is stored as CH_4, and two moles of oxygen demand are consumed in the combustion of CH_4:

$$CH_4 + 2O_2 \rightarrow CO_2 + H_2O \tag{2}$$

Two moles of oxygen demand removed from the system thus represent one mole of CH_4 produced. The volume of methane produced can then be determined by calculating the moles of oxygen demand contained in the biogas CH_4 and applying the ideal gas law. A spreadsheet program was used to execute a mass balance based on equation 1. Flushed manure, lagoon effluent, decant liquid, and mixed liquor COD results were used to estimate oxygen demand. Since VS was analyzed more frequently than COD, the mass of organic matter leaving or entering on any day was determined by linear interpolation between VS results. Volatile solids were converted to oxygen demand by multiplying the daily VS concentration by a rolling average of COD/VS using the closest four samples to the day in question (two samples before and two samples after day *i*).

ASBR OPERATIONAL PARAMETERS

The ASBR controller set the react and settling phase length, as well as the liquid height in the ASBR at the end of filling and decanting. These controls were used to set the number of cycles per day, settling time, react time, volume of the reactor during the react phase, volume of effluent added, volume of liquid decanted, and HRT. Determining the operational parameters (HRT, SRT, and OLR) is more complicated for ASBR digesters than for complete-mix digesters due to the sequential batch operation and the fact that decanted liquid and sludge are removed at different intervals. Hydraulic retention was calculated daily using equation 3:

$$\text{HRT} = \text{VRP}_i \, / \, \tilde{\text{V}}\text{DT}_i \tag{3}$$

where

HRT = hydraulic retention time (days)

VRP_i = volume of reactor during the react phase on day i (m^3)

$\tilde{\text{V}}\text{DT}_i$ = volume decanted on day i ($\text{m}^3\ \text{d}^{-1}$).

Solids retention time (SRT) was calculated by dividing the average mass of VSS held in the reactor over an extended period of time by the masses of VSS leaving the reactor with decant liquid and sludge for the same time period (eq. 4):

$$\text{SRT} = \frac{\left(\sum_{1}^{n} \frac{\left(\text{VRP}_i \times \text{MLVSS}_i\right)}{n}\right)}{\left(\sum_{1}^{n}\left(\tilde{\text{V}}\text{DT}_i \times \text{DTVSS}_i\right) + \sum_{1}^{x}\left(\tilde{\text{V}}\text{SL}_j \times \text{SLVSS}_j\right)\right)} \tag{4}$$

where

SRT = solids retention time (days)

$MLVSS_i$ = mixed liquor volatile suspended solids concentration on day i (kg m^{-3})
n = number of days in observation period
$DTVSS_i$ = decant volatile suspended solids concentration on day i (kg m^{-3})
$\tilde{V}SL_j$ = volume of sludge wasted during event j (m^3)
$SLVSS_j$ = sludge volatile suspended solids concentration during wasting event j (kg m^{-3})
x = number of sludge wasting events during observation period.

The number of days in the observation period (n) always exceeded 3 × HRT when calculating SRT.

All the manure produced on the farm passed through the ASBR. The mass and quality of organic matter entering the equalization tank depended on the number of animals housed on the farm and the type of buildings contributing manure to lift station 1 each day. Organic loading rate (OLR), or the mass of organic matter loaded per reactor volume, was calculated daily using equation 5:

$$\mathrm{OLR} = \frac{\left(\tilde{V}\mathrm{IN}_i \times \mathrm{INVS}_i\right)}{\mathrm{VRP}_i} \tag{5}$$

where
OLR = organic loading rate (kg VS m^{-3} d^{-1})
$\tilde{V}IN_i$ = volume of influent entering reactor on day i (m^3 d^{-1})
$INVS_i$ = influent volatile solids concentration measured on day i (kg VS m^{-3}).

ASBR PERFORMANCE PARAMETERS

Organic matter stability and biogas production were measured using two parameters: organic matter removal efficiency (OMRE) and methane yield (MY). The way in which OMRE was calculated deviated slightly from ASERTTI protocols for complete-mix and plug-flow digesters (ASERTTI, 2007). Removal efficiency was defined in this study as the ability of the reactor to remove organic matter from the liquid stream. In an ASBR, this depends on both organic matter conversion to biogas and settling, whereas removal by settling is not considered in plug-flow and complete-mix digesters (ASERTTI, 2007). Organic matter removal efficiency was calculated using equation 6:

$$\mathrm{OMRE} = 100 \times \frac{\left(\sum_{1}^{n}\left(\tilde{V}\mathrm{IN}_i \times \mathrm{INOM}_i\right) - \sum_{1}^{n}\left(\tilde{V}\mathrm{DT}_i \times \mathrm{DTOM}_i\right)\right)}{\left(\sum_{1}^{n}\left(\tilde{V}\mathrm{IN}_i \times \mathrm{INOM}_i\right)\right)} \tag{6}$$

where
OMRE = organic matter removal efficiency (%)
$DTOM_i$ = decant organic matter concentration on day i.

Efficiency of the digestion process was measured as MY in a manner identical to that outlined in the ASERTTI protocol (ASERTTI, 2007):

$$\mathrm{MY} = \frac{\left(\sum_{1}^{n}\left[\frac{\tilde{V}\mathrm{CH4}_i}{(\tilde{V}\mathrm{IN}_i \times \mathrm{INOM}_i)}\right]\right)}{n} \tag{7}$$

where
MY = average methane yield (m^3 CH$_4$ kg^{-1})
$\tilde{V}CH4_i$ = volume of methane produced on day i (m^3 d^{-1})
$INOM_i$ = influent organic matter concentration measured on day i (kg m^{-3}).

One more measure of reactor efficiency was used in this study, volumetric reactor efficiency (VRE). This was calculated by dividing daily CH_4 production by reactor volume during the react phase:

$$\mathrm{VRE} = \frac{\left(\sum_{1}^{n}\left(\tilde{V}\mathrm{CH4}_i \,/\, \mathrm{VRP}_i\right)\right)}{n} \tag{8}$$

ASBR OPERATION

The full-scale reactor was started on 8 August 2008 using a cold-start technique (Steele and Hamilton, 2009). Between 2 February and 31 March 2009, adjustments were made to mixing and settling time, and to reduce crusting in the reactor. Reactor performance was intensely monitored between 1 April 2009 and 22 April 2010. The reactor was operated in three regimes during the monitoring period. Between 1 April and 19 July 2009, the ASBR was loaded with manure as it was flushed from the building at a 20-day HRT. Between 7 December 2009 and 22 April 2010, the ASBR was operated at 5-day HRT to maximize biogas production. The ASBR transitioned between the two conditions from 20 July to 6 December 2009. Operational parameters used during the three periods are given in table 1.

RESULTS AND DISCUSSION

SAMPLING RESULTS

Analyses of manure samples collected throughout ASBR operation are given in table 2. Average solids and COD analyses of influent, mixed liquor, and decant liquid for each operational period are given in table 3. Influent TS concentration in the 5-day HRT period was approximately 40% that of the 20-day HRT period. This is due to the fact that 7 m^3 of lagoon effluent were added for each 3 m^3 of manure flushed from the building to provide sufficient volume to maintain the 5-day HRT. COD analyses were not performed during the 5-day HRT period. The values shown in table 2 were estimated based on VS and the COD:VS ratio of the last four samples of the transitional period. Reactor pH remained in the range 6.55 to 7.30 throughout the monitoring period.

SOLIDS LOADING AND ACCUMULATION

Organic loading rate and the mass of VS leaving the reactor each day with decant liquid are plotted in figure 3. These results are the daily calculated values determined using influent and decant volumes and linear interpolation

Table 1. Operational parameters used during the period of observation.

Operational Period	Start and End Dates	Days after Reactor Startup	HRT (days)	Cycles per Day	Temp. Range (°C)	Liquid Height in Reactor (m)		Volume during React (m^3)	Liquid Added (m^3 d^{-1})	
						During React	End of Decant		Flushed Manure	Lagoon Effluent
20-day HRT	1 Apr. to 19 July 2009	236-342	20	1	22-32	3.51	3.33	406	20.3	0.0
Transition	20 to 26 July 2009	343-350	19	1	32	3.29	3.12	381	20.0	0.0
	27 July to 2 Aug. 2009	351-358	18	1	32	3.10	2.93	359.5	20.0	0.0
	3 to 9 Aug. 2009	359-366	17	1	31	2.92	2.75	338	19.9	0.0
	10 to 16 Aug. 2009	367-374	16	2	31	2.74	2.65	317	19.8	0.0
	17 Aug. to 13 Sept. 2009	374-402	15	2	30	2.75	2.65	318	21.2	0.0
	14 to 21 Sept. 2009	403-411	14	2	30-26	2.75	2.65	318.5	18.5	4.25
	22 to 27 Sept. 2009	412-417	13	2	26-20	2.76	2.65	320	19.7	4.9
	28 Sept. to 4 Oct. 2009	418-425	12	2	24-22	2.77	2.65	321	20.0	6.7
	5 to 11 Oct. 2009	426-433	11	2	22-20	2.78	2.65	322	17.25	12.0
	12 Oct. to 12 Nov. 2009	434-465	10	2	20-24	2.79	2.65	323	19.0	13.3
	13 to 16 Nov. 2009	465-469	9	2	24	2.81	2.61	325	20.2	15.8
	17 to 24 Nov. 2009	469-476	8	2	24	2.81	2.63	325	19.9	20.8
	25 Nov. to 1 Dec. 2009	477-483	7	2	24	2.81	2.61	325	20.0	26.5
	2 to 6 Dec. 2009	484-488	6	2	24	2.90	2.65	335	17.3	38.5
5-day HRT	7 Dec. 2009 to 22 Apr. 2010	489-625	5	2	24-22	2.95	2.65	341	19.8	48.4

Table 2. Characteristics of flushed manure and recycled lagoon effluent fed to the reactor (SD = standard deviation).

	Manure			Lagoon Effluent		
Characteristic	*n*	Avg.	SD	*n*	Avg.	SD
TS (mg L^{-1})	20	9000	2200	4	750	370
VS (mg L^{-1})	20	6400	1800	4	330	47
TSS (mg L^{-1})	5	6300	1900	N/A	N/A	N/A
VSS (mg L^{-1})	3	4600	650	N/A	N/A	N/A
COD (mg L^{-1})	13	14,000	4000	4	260	86
NH_3-N (mg L^{-1})	2	511		N/A	N/A	N/A
pH	18	6.8	0.24	4	6.0	0.58

between VS samples. The masses of solids species (TS, VS, TFS) held in the reactor with mixed liquor are shown in figure 4. Sludge was not intentionally wasted during the study period. However, four unintentional wastings occurred due to ultrasonic meter malfunctions that decanted liquids during the react phase. The mass of reactor solids lost was calculated by multiplying the volume accidentally decanted by the mixed liquor solids content. In figure 4, the calculated masses of VS leaving the reactor with each wasting are shown above arrows indicating the time of solids loss. Solids gradually accumulated in the reactor up to the time influent reached a 50:50 mixture of flushed manure and lagoon effluent. After November 2009, there was a trend toward solids washing out of the reactor, although it appears the washout of solids stabilized by April 2010.

BIOGAS PRODUCTION

Biogas monitoring proved to be problematic. Leaks caused by tears and hail damage to the flexible membrane cover resulted in recorded values that underestimated biogas production. The rotary gas meter also failed to provide reliable results. Fine particles and ice routinely fouled the meter, and less than perfectly level mounting caused damage to the rotor. In September 2009, the gas meter failed altogether.

The biogas production estimated by the mass balance is compared to measurements made by the rotary gas meter in figure 5. Ambient temperature and atmospheric pressure measured on the day of measurement were used in the ideal gas law to determine the volume of CH_4 produced. Daily CH_4 production predicted by the model was converted to biogas by dividing the volume of CH_4 by 0.66. This volume fraction of CH_4 in biogas was determined using laboratory reactors and the same source of manure used in this study (Hamilton, 2013). The calculated biogas production follows the trend of the measured data. In addition, the modeled biogas production closely follows OLR (fig. 5). Values calculated by the mass balance are generally higher than measured values, which indicates that the measured data underestimated biogas production due to cover leaks and meter malfunctions.

Table 3. Influent, mixed liquor, and decant solids and COD concentrations for each sampling period.[a]

Sampling Period	TS			VS			TSS			VSS			COD		
	n	Avg.	SD	*n*	Avg.	SD	*n*	Avg.	SD	*n*	Avg.	SD	*n*	Avg.	SD
Influent															
20-day HRT	14	9100	2500	27	8900	2600	5	6300	1900	3	4600	1300	12	14,000	3000
Transitional	27	8900	2600	27	6600	2000	6	6600	1900	4	5200	1300	15	15,000	4150
5-day HRT	3	3900	890	3	2400	690	N/A	N/A		N/A	N/A	-		4300[b]	
Mixed liquor															
20-day HRT	13	6200	860	13	4100	390	6	4200	390	3	3500	220	10	5950	610
Transitional	25	8100	1800	24	5600	1400	19	6550	1700	16	5600	1200	16	8200	2600
5-day HRT	5	6950	930	5	4750	780	5	5100	1100	4	3850	300		6900[c]	
Decant															
20-day HRT	13	4100	1100	13	2400	920	6	2800	770	3	2400	600	11	4300	1400
Transitional	25	4100	1600	25	2300	1200	20	2300	1600	17	1800	1300	13	4500	1600
5-day HRT	3	2600	383	3	1100	200	2	1100		2	720			1900[d]	

[a] Avg. = average (mg L^{-1}), SD = standard deviation (mg L^{-1}), and N/A = not applicable.

[b] VS × 1.83.

[c] VS × 1.45.

[d] VS × 1.74.

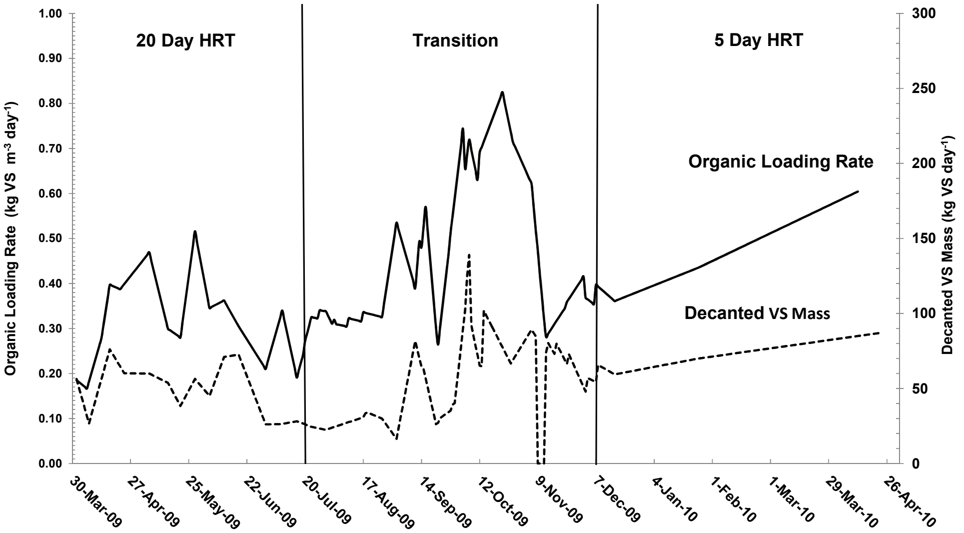

Figure 3. Organic matter loading rate and mass of VS leaving each day with decant liquid.

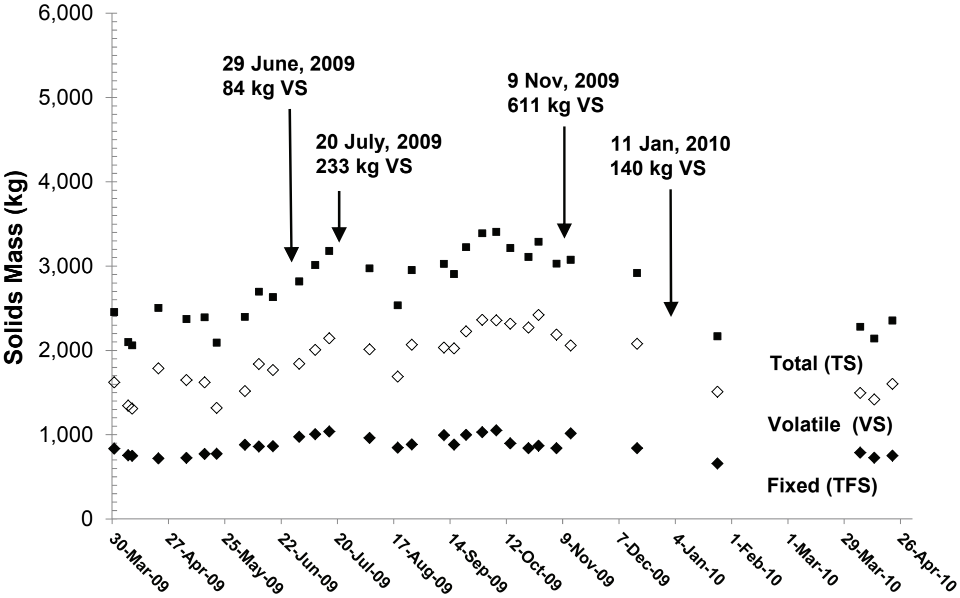

Figure 4. Mass of solids retained in the reactor and masses of VS lost with accidental sludge wastings. Date and mass of solids estimated to be lost with each sludge wasting are shown above arrows indicating the time of wasting.

MEASURES OF ASBR PERFORMANCE

Performance parameters calculated for the 20-day HRT and 5-day HRT operational periods are given in table 4. Organic loading rate was higher during the 5-day HRT than the 20-day HRT period. Two factors contributed to this. First, volume during the react phase was 406 m^3 during 20-day HRT operation and 341 m^3 during 5-day HRT operation. Secondly, more finishers were housed on the farm during 5-day HRT operation. The VS added with lagoon effluent had only a minor effect on OLR. Lagoon effluent VS contributed 7.5% to 11% of the total influent VS mass during 5-day operation. Parameters that involved CH_4 production (MY and VRE) were calculated using the organic matter mass balance with CH_4 volumes at 20°C and 1 atm.

Organic Matter Conversion to Methane

Methane yield during 5-day HRT operation was lower than during 20-day HRT, but these results were expected given the shorter SRT and lower reactor temperature during 5-day HRT operation. The methane yields measured in this study are higher than those achieved by Ndegwa et al. (2005) in the laboratory. Comparison cannot be made for the 20-day HRT operational period because an HRT of 20 days was outside the range of data used in the laboratory experiments (4 to 12 days HRT). The methane yield for laboratory reactors under conditions similar to 5-day HRT operation of the farm-scale reactor (HRT = 5 days, OLR = 0.55 kg VS m^{-3} d^{-1}, 20°C) was 0.17 m^3 CH_4 kg^{-1} VS. Therefore, the methane yield of the farm-scale reactor was more than twice that of the laboratory reactors of Ndegwa et al. (2005). Methane yields achieved by the farm-scale reactor approached those measured in the laboratory by Angenent et al. (2002) and Zhang et al. (1997) using manure with higher solids content.

Conversion to biogas accounts for nearly all of the COD

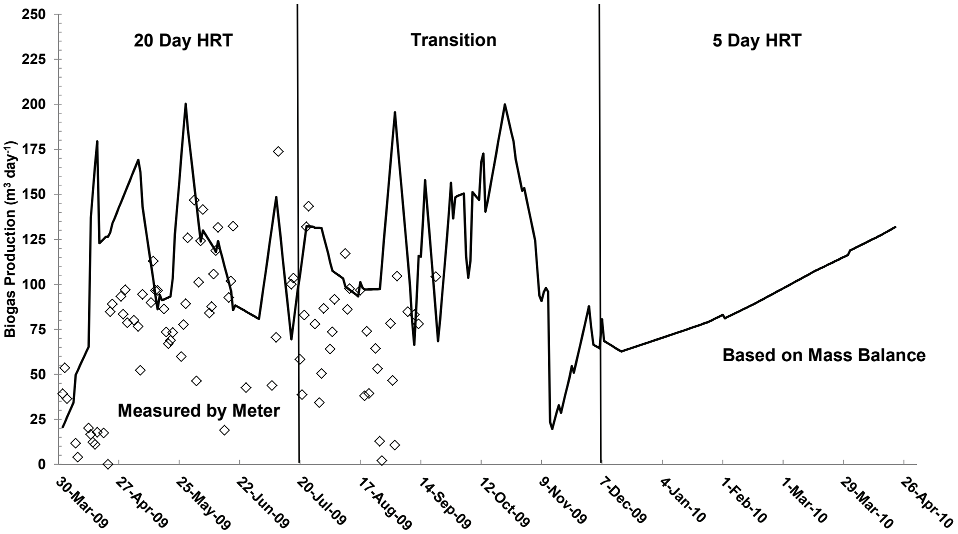

Figure 5. Daily biogas production measured by rotary meter and calculated using an organic matter mass balance.

Table 4. Performance parameters measured on the farm-scale reactor during 20-day and 5-day HRT operation.

			Operational Period	
Parameter	Abbreviation	Units	20-Day HRT	5-Day HRT
Organic loading rate	OLR	kg VS m^{-3} d^{-1}	0.32	0.48
Solids retention time	SRT	days	51	26
VS removal efficiency	OMRE	%	62	55
COD removal efficiency	OMRE	%	73	57
VS methane yield	MY	m^3 CH_4 kg^{-1} VS	0.55	0.38
COD methane yield	MY	m^3 CH_4 kg^{-1} COD	0.25	0.21
Volumetric reactor efficiency	VRE	m^3 CH_4 m^{-3} d^{-1}	0.18	0.18

removal in the farm-scale reactor. Assuming that the COD test completely measures the organic matter content of a substrate, and 1 mole of organic matter yields 2 moles of CH_4 (eq. 2), then the ultimate methane yield of 1 kg of COD at 20°C and 1 atm is 0.38 m^3 CH_4 kg^{-1} COD. Therefore, the methane yield of 0.25 m^3 CH_4 kg^{-1} COD observed during 20-day HRT operation represents 66% of the ultimate methane yield of swine manure. Likewise, the 0.21 m^3 CH_4 kg^{-1} COD value for the 5-day HRT period represents 55% of the ultimate methane yield.

Organic Matter Removal by Settling

The organic matter removal efficiency, which depends on both settling and organic matter conversion to biogas, was lower than that achieved in the laboratory by Ndegwa et al. (2005). Laboratory reactors operated under similar conditions as the 5-day HRT operation (HRT = 5 days, OLR = 0.55 kg VS m^{-3} d^{-1}, 20°C) achieved a COD OMRE of 89%.

As demonstrated in the previous section, if the fraction of COD removed as methane is subtracted from OMRE, only 7% of COD was removed by settling during 20-day HRT operation, and barely 3% was removed by settling during 5-day HRT operation. One reason for the poor settling was that the mixed liquor TS did not reach 1.0% TS, which is considered optimal for settling swine manure solids (Ndegwa et al., 2001). This can be partially attributed to the cold-start technique used to start the ASBR. Only dilute swine manure was used to inoculate the reactor during startup; therefore, the solids content of the mixed liquor was less than ideal from the beginning, and the reactor was never able to reach a critical mass of suspended solids. The mixed liquor TS concentration came close to 1.0% during 20-day HRT operation, and this may explain the better OMRE performance compared to the 5-day HRT operation. The reactor was beginning to recover solids after five months of dilute influent addition during April 2010, and OMRE should have improved as the mixed liquor TS mass in the reactor continued to increase. Another factor contributing to poor settling was that the aggressive mixing technique (i.e., passing the mixed liquor through a centrifugal pump and ejecting it in a high-velocity jet) may have reduced aggregation of reactor solids. Ndegwa et al. (2005, 2008) used a peristaltic pump and much lower flow velocities to mix their laboratory reactors.

Reactor Efficiency

Volumetric reactor efficiency (VRE) was identical during both 20-day and 5-day HRT operation, even though methane yield was higher during 20-day HRT operation. These results can be explained using microbial kinetics. Chen and Hashimoto (1980) developed a model for methane production in continuously stirred reactors based on Contois kinetics. This model can be adapted to an ASBR digester by using separate terms for HRT and SRT, as shown in equation 9:

$$\text{VRE} = \left(\frac{B_0 \times S_0}{\text{HRT}}\right) \times \left(1 - \frac{K}{(\mu \times \text{SRT} - 1 + K)}\right) \qquad (9)$$

where

B_0 = maximum methane yield (m^3 CH_4 kg^{-1} VS)

S_0 = substrate concentration (kg VS m^{-3})

K = kinetic parameter

μ = specific growth rate (d^{-1}).

Maximum methane yield (B_0) is not identical to ultimate yield but is instead the highest yield expected under ideal conditions. Using the kinetic and microbial growth parameters determined by Hashimoto (1983) for swine manure, an S_0 equal to 8.9 kg VS m^{-3} (table 2), an SRT equal to 51 days (table 4), and VRE equal to 0.18 m^3 CH_4 m^{-3} d^{-1} (table 4) gives B_0 equal to 0.42 m^3 CH_4 kg^{-1} VS for the 20-day HRT period. Assuming that B_0 in the 5-day HRT is also 0.42 m^3 CH_4 kg^{-1} VS and using S_0 and SRT values from tables 2 and 4 for the 5-day HRT period in equation 9 gives VRE equal to 0.20 m^3 CH_4 m^{-3} d^{-1}. This is slightly higher than the 0.18 m^3 CH_4 m^{-3} d^{-1} measured. Actual B_0 during the 5-day HRT operation may have been lower than 0.42 m^3 CH_4 kg^{-1} VS. Lagoon effluent organic matter contained less energy (COD/VS = 0.79) than flushed manure (COD/VS = 2.2), and the additional 7.5% to 11% VS added with lagoon effluent may have reduced maximum methane yield. The lagoon effluent also diluted S_0 during 5-day HRT operation. Had the reactor volume been reduced rather than lagoon effluent added to achieve 5-day HRT, then the VRE calculated using equation 9 with S_0 equal to 8.9 kg VS m^{-3} would be 0.67 m^3 CH_4 m^{-3} d^{-1} at 23°C, and 0.70 m^3 CH_4 m^{-3} d^{-1} at 30°C. If settling could be improved to bring SRT to 51 days, then the VRE at 30°C would be further increased to 0.73 m^3 CH_4 m^{-3} d^{-1}.

CONCLUSIONS

Methane production achieved by a 400 m^3 farm-scale ASBR digester treating dilute swine manure was much higher than expected based on laboratory studies of similar substrate. Methane yield at 20-day HRT, 51-day SRT, 0.32 kg VS m^{-3} OLR, and reactor temperature between 22°C and 32°C was 0.55 m^3 CH_4 kg^{-1} VS. Methane yield at 5-day HRT, 26-day SRT, 0.48 kg VS m^{-3} OLR, and reactor temperature between 22°C and 24°C was 0.38 m^3 CH_4 kg^{-1} VS. Volumetric reactor efficiency was 0.18 m^3 CH_4 m^{-3} d^{-1} for both 5-day and 20-day HRT operating conditions. Had the reactor volume been decreased to achieve 5-day HRT with only flushed manure, microbial kinetics models predicted that the volumetric reactor efficiency would have been greater than 0.70 m^3 CH_4 m^{-3} d^{-1}.

Organic matter removal efficiency was lower than the 85% COD removal design target. Removal efficiency during 20-day HRT operation was 62% for VS and 73% for COD. Removal efficiency during 5-day HRT operation was 55% for VS and 57% COD. It appears that almost all of the organic matter removal was due to conversion of organic matter to biogas, and very little was due to settling.

Overall, the reactor microbiology was robust. Despite changes to reactor operating parameters, accidental sludge wasting, fluctuating OLR, and seasonal temperature variation, the ASBR never lost gas production, and reactor pH remained neutral (6.55 to 7.30). Construction of ASBR covers should be improved to withstand the stresses placed on the reactor due to cyclic loading and decanting of liquid. Clearly, the unsupported membrane cover used in this application failed to withstand these forces and to resist the inclement weather typical of Oklahoma.

ACKNOWLEDGEMENTS

The authors would like to thank the OSU Animal Science Department for use of the Oklahoma Swine Research and Education Center. We would especially like to thank Dr. Scott Carter, associate professor of swine nutrition, Mr. Kim Brock, farm operations coordinator, and Mr. John Staude, OSU SREC herd manager. Funding for this project was made available by the Oklahoma Cooperative Extension Service and the USDA National Institute for Food and Agriculture.

REFERENCES

Angenent, L. T., Sung, S., & Raskin, L. (2002). Methane yield and methanogen levels of ASBR systems treating swine waste: Effect of different inocula. In *Proc. 7th Latin American Workshop and Symp. on Anaerobic Digestion (LAAD)*. London, U.K.: International Water Association.

APHA. (1998). *Standard Methods for the Examination of Water and Wastewater* (20th ed.). Washington, D.C.: American Public Health Association.

ASERTTI. (2007). A protocol for quantifying and reporting the performance of anaerobic digestion systems for livestock manures. Pullman, Wash.: Association of State Energy Research and Technology Transfer Institutions.

Chen, Y. R., & Hashimoto, A. G. (1980). Substrate utilization kinetic model for biological treatment processes. *Biotech. Bioenergy, 22*(10), 2081-2095. http://dx.doi.org/10.1002/bit.260221008.

Hamilton, D. W. (2013). Using glycerol, a byproduct of biodiesel creation from soybeans, to increase the energy recovery from anaerobic digesters. Final report to Oklahoma Soybean Board. Claremore, Okla.: Oklahoma Soybean Board.

Hamilton, D. W., Kizer, M. A., Steele, M. T., Frazier, R. S., Carter, S. D., Brock, K. S., & Williamson, R. D. (2010). Oklahoma State University Swine Research and Education Center manure handling and utilization. In *Proc. Intl. Symp. on Air Quality and Manure Mgmt. for Agriculture*. St Joseph, Mich.: ASABE.

Hansen, K. H., Angelidaki, I., & Ahring, B. K. (1999). Improving thermophilic anaerobic digestion of swine manure. *Water Res., 33*(8), 1805-1810. http://dx.doi.org/10.1016/S0043-1354(98)00410-2.

Hashimoto, A. G. (1983). Thermophilic and mesophilic anaerobic fermentation of swine manure. *Agric. Wastes, 6*(3), 175-191. http://dx.doi.org/10.1016/0141-4607(83)90085-9.

Kramer, J. M. (2002). *Agricultural Biogas Casebook*. Madison, Wisc.: Resource Strategies, Inc.

Kramer, J. M. (2004). *Agricultural Biogas Casebook: 2004 Update*. Madison, Wisc.: Resource Strategies, Inc.

Kramer, J. M., & Bilek, A. (2013). Anaerobic digestion on swine operations: Assessing current barriers and future opportunities. Madison, Wisc.: Energy Center of Wisconsin.

Ndegwa, P. M., Zhu, J., & Luo, A. (2001). Effects of solids levels and chemical additive on removal of solids and phosphorus in swine manure. *J. Environ. Eng., 127*(12), 1111-1115. http://dx.doi.org/10.1061/(ASCE)0733-9372(2001)127:12(1111).

Ndegwa, P. M., Hamilton, D. W., Lalman, J. A., & Cumba, H. J. (2005). Optimization of anaerobic sequencing batch reactors treating dilute swine manure. *Trans. ASAE, 48*(4), 1575-1583.

http://dx.doi.org/10.13031/2013.19191.

Ndegwa, P. M., Hamilton, D. W., Lalman, J. A., & Cumba, H. J. (2008). Effects of cycle frequency and temperature on the performance of anaerobic sequencing batch reactors (ASBR) treating swine waste. *Bioresource Tech., 99*(6), 1972-1980. http://dx.doi.org/10.1016/j.biortech.2007.03.056.

Steele, M. T., & Hamilton, D. W. (2009). Start-up of an anaerobic sequencing batch reactor (ASBR) treating low-strength swine manure. ASABE Paper No. 096766. St Joseph, Mich.: ASAE.

Sung, S., & Dague, R. (1995). Laboratory studies on the anaerobic sequencing batch reactor. *Water Environ. Res., 67*(3), 294-301. http://dx.doi.org/10.2175/106143095X131501.

USEPA. (2014). Operating anaerobic digester projects. Washington, D.C.: USEPA AgStar Program. Retrieved from www.epa.gov/agstar/projects/index.html.

Wang, Z., Wang, W., Zhang, X., & Zhang, G. (2009). Digestion of thermally hydrolyzed sewage sludge by anaerobic sequencing batch reactor. *J. Hazardous Materials, 162*(2-3), 799-803. http://dx.doi.org/10.1016/j.jhazmat.2008.05.103.

Zhang, R. H., Yin, Y., Sung, S., & Dague, R. R. (1997). Anaerobic treatment of swine waste by the anaerobic sequencing batch reactor. *Trans. ASAE, 40*(3), 761-767. http://dx.doi.org/10.13031/2013.21307.