Energies **2010**, *3*, 974-988; doi:10.3390/en3050974

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Simulation of the Impact of SRT on Anaerobic Digestability of Ultrasonicated Hog Manure

Elsayed Elbeshbishy [1], Angel Nakevski [2], Hisham Hafez [1], Madhumita Ray [2]* and George Nakhla [1, 2]

[1] Department of Civil and Environmental Engineering, University of Western Ontario, London, Ontario N6A 5B9, Canada; E-Mails: eelbeshb@uwo.ca (E.E.); hhafez@uwo.ca (H.H.); gnakhla@eng.uwo.ca (G.N.)

[2] Department of Chemical and Biochemical Engineering, University of Western Ontario, London, Ontario N6A 5B9, Canada; E-Mail: anakevsk@uwo.ca

* Author to whom correspondence should be addressed; E-Mail: mray@eng.uwo.ca; Tel.: +1-519-661-2111-x81273; Fax: +1-519-661-3498.

Received: 26 March 2010 / Accepted: 15 April 2010 / Published: 11 May 2010

Abstract: Ultrasonication at a specific energy of 500 kJ/kgTS was applied to hog manure in a continuous mode completely mixed anaerobic digestion. A process model in BioWin was developed, calibrated and tested at different solids retention times (SRTs) to evaluate the process economics. The results showed that there was a 36% increase in volatile suspended solids (VSS) removal efficiency, a 20% increase in methane production rate, a 13.5% increase in destruction of bound proteins, and a reduction from 988 to 566 ppm in H_2S concentration in the digester headspace. Furthermore, a calibrated model of the process using BioWin to assess the impact of SRTs on the economics of anaerobic digestion for unsonicated and sonicated hog manure revealed that ultrasonication resulted in a net benefit of $42–46/ton dry solids at SRTs of 15–30 days.

Keywords: anaerobic digestion; SRT; ultrasound; hog manure; bound protein

Nomenclature

AD	Anaerobic digestion
B-Protein	Bound protein
L_{CH4}	Litre of CH_4

L_r	Litre of reactor
P	Ultrasonic power
P-Protein	Particulate protein
SCOD	Soluble chemical oxygen demand
SE	Specific energy input
S-Protein	Soluble protein
SRT	Solids retention time
SRTs	Solids retention times
STKN	Soluble total Kjeldahl nitrogen
t	Ultrasonic duration
TCOD	Total chemical oxygen demand
TKN	Total Kjeldahl nitrogen
TS	Total solids
TSS	Total suspended solids
V	Volume of sonicated manure
VFA	Volatile fatty acids
VSS	Volatile suspended solids
WAS	Waste-activated sludge

1. Introduction

Although swine wastewater is widely used as fertilizer because of its high organic, nitrogen and phosphorus content, many countries are paying attention to the pollution resulting from livestock farms, and have tightened legislation and discharge standards recently. As far as swine waste treatment is concerned, anaerobic digestion (AD) is an important alternative to land application, because it reduces pollution and recovers methane. A number of studies have been reported for anaerobic digestion of swine waste [1-4] in the literature.

In general, the limiting step of anaerobic digestion of solid waste is the first step of hydrolysis or solubilization, where the cell wall is broken down allowing the organic matter inside the cell to be available for biological degradation [5-8]. Particularly, in the case of livestock residues, the hydrolysis step is restricted by the presence of fibres [9]. The anaerobic digestion process may therefore be improved if hydrolysis can be enhanced. Thus, pretreatment is often required in order to achieve the release of lignocellulosic material and thus accelerate the degradation process by means of waste solubilization and consequently enhance the biogas production during anaerobic digestion [9]. Various pretreatment methods such as thermal, chemical, ultrasonic, and biological have been studied by many researchers [10-13]. Since the hydrolysis rate is directly related to the surface area of the sludge particles [14], increasing particles surface area will also increase the hydrolysis rate [15]. The use of ultrasonication in the pretreatment of sludge improved the operational reliability of anaerobic digesters, decreased odor generation and clogging problems and enhanced sludge dewatering [16].

It must be noted that while H_2S has been accepted as the main odorous contaminant in biogas, recently bound proteins *i.e.*, proteins loosely attached to the cell wall, have been determined as a major odor precursor downstream of anaerobic digestion, specifically during dewatering. Despite the numerous advantages of ultrasonic pretreatment of municipal biosolids, operational reliability, ease of implementation, elimination of odors and clogging, and good sludge dewaterability, the rapid wear on the sonotrode and negative energy balance [17] hindered widespread use of the technology.

The presence of high sulfate concentration in wastewater restricts the application of the anaerobic digestion treatment technology due to the production of the toxic and odorous hydrogen sulfide (H_2S) by sulfate-reducing bacteria [18]. The extensive ultrasonication research available in the open literature focused primarily on improving hydrolysis of municipal biosolids, with little or sparse data on applications to other wastes and impact on odor. Thus, the aim of this study is to investigate the effect of ultrasonication of hog manure on the performance of anaerobic digestion and its effect in odor reduction, specifically the removal of bound protein and hydrogen sulfide in the headspace.

2. Experimental Section

2.1. Analytical methods

Samples were analyzed for total suspended solids (TSS), volatile suspended solids (VSS), total Kjeldahl nitrogen (TKN), and soluble total Kjeldahl nitrogen (STKN) using standard methods [19]. Total and soluble chemical oxygen demand (TCOD, SCOD) and ammonia (NH_4-N) were measured using HACH equipment (HACH Odyssey Analyzer and COD heating reactor) using standard HACH testing kits for different analyses. Soluble parameters were determined after filtering the samples through 0.45 µm filter paper. The produced biogas was collected by wet tip (Gas meters for laboratories, Nashville, TN). The gas meter consists of a volumetric cell for gas-liquid displacement, a sensor device for liquid level detection, and an electronic control circuit for data processing and display (Speece, 1996) [20]. Biogas composition was determined by a gas chromatograph (Model 310, SRI Instruments, Torrance, CA) equipped with a thermal conductivity detector (TCD) and a molecular sieve column (Molesieve 5A, mesh 80/100, 182.88 × 0.3175 cm). The temperatures of the column and the TCD detector were 90 and 105 °C, respectively. Argon was used as carrier gas at a flowrate of 30 mL/min. H_2S was measured using the Odalog (model odalog type I, App-Tek International Pty Ltd, Brendale 4500, Australia), which has a detection range of 0–1000 ppm with an accuracy of 2 ppm. SO_4^{2-} was measured using an ion chromatography (IC) system (Dionex 600, USA) equipped with CS16-HC and AS9- HC columns, respectively.

2.2. Protein measurement

Protein was determined by micro-bicinchoninic acid protein assay (Pierce, Rockford, USA), which was modified by Lowry *et al.* [21] using standard solution of bovine serum albumin. Cell protein was calculated as the difference between particulate and bound protein. In order to measure proteins, 50 mL samples were centrifuged at 10,000 rpm for 15 minutes at 5 °C to separate the liquid and solids in the sample. The supernatant was filtered through a 1.5 µm glass microfiber filter and the filtrate was analyzed for the soluble protein fraction. Bound protein was extracted from the suspended solids by mild pH 8 phosphate buffers (50 mM), while particulate protein representing both the bound protein adsorbed on biomass and the protein within the biomass was extracted by an alkaline 1 N NaOH solution [21]. The solids from the filter were resuspended to a total volume of 50 mL with pH 8 phosphate buffer (50 mM) for measuring bound protein and 1 N NaOH for particulate protein. The solution was mixed using a magnetic stirrer at 1500 rpm for 10 minutes, and centrifuged at 10,000 rpm for 15 minutes at 5 °C, with the centrate filtered through a 1.5 μm glass microfiber filter, prior to protein analysis.

2.3. Ultrasonication and anaerobic digestion set-up

A lab scale ultrasonic probe was used to treat hog manure obtained from local hog farm in Southwestern, Ontario, Canada. The ultrasonic probe was supplied by Sonic and Materials (model VC-500, 500 W, and 20 kHz). Hog manure was sonicated with specific energy inputs of 500 kJ/kgTS, with sonication pulses set to 2 seconds on and 2 seconds off to control the temperature rise of the sludge. Digestion of hog manure was carried out using anaerobic digester (10 L), with a working volume of 7.5 L and a solids retention time (SRT) of 15 days, operated in completely mixed continuous flow mode and maintained at constant temperature of 37 °C. Table 1 lists the feed characteristics used for the unsonicated and sonicated runs. The digester was operated at steady-state, as reflected by constant specific biogas production rate and digester sludge biomass concentration (was reached after more than three turnovers of the mean SRT).

Table 1. Feed characteristics used for the unsonicated and sonicated manure.

Parameter (mg/L)	Unsonicated manure (influent to the control digester)	Sonicated manure	
		Manure before sonication	Manure after sonication (influent to the digester)
TSS	15,119 ± 552	15,792 ± 680	13,916 ± 785
VSS	11,000 ± 526	11,496 ± 510	8816 ± 411
TCOD	26,638 ± 1829	28,000 ± 1540	28,333 ± 1471
SCOD	12,645 ± 1238	13,050 ± 1260	15,854 ± 1289
Ammonia	753 ± 30	824 ± 88	464 ± 71
P-Protein	2671 ± 87	2854 ± 210	2569 ± 183
B-Protein	675 ± 73	708 ± 62	623 ± 76
S-Protein	2613 ± 188	2920 ± 360	3416 ± 210
TKN	1779 ± 89	1879 ± 98	1800 ± 107
STKN	939 ± 108	939 ± 66	1054 ± 44
VFA*	1650 ± 187	1680 ± 308	1797 ± 257

*VFA in mgCOD/L

2.4. Specific energy input

The specific energy input (SE) is a function of ultrasonic power, ultrasonic duration, and volume of sonicated sludge and TS concentration, and can be calculated using the following equation Bougrier *et al.* [22]:

$$SE = \frac{P \times t}{V \times TS} \tag{1}$$

where *SE* is the specific energy input in kWs/kgTS (kJ/kgTS), P is the ultrasonic power in kW, t is the ultrasonic duration in seconds, V is the volume of sonicated sludge in litres, and TS is the total solids concentration in kg/L.

3. Results and Discussion

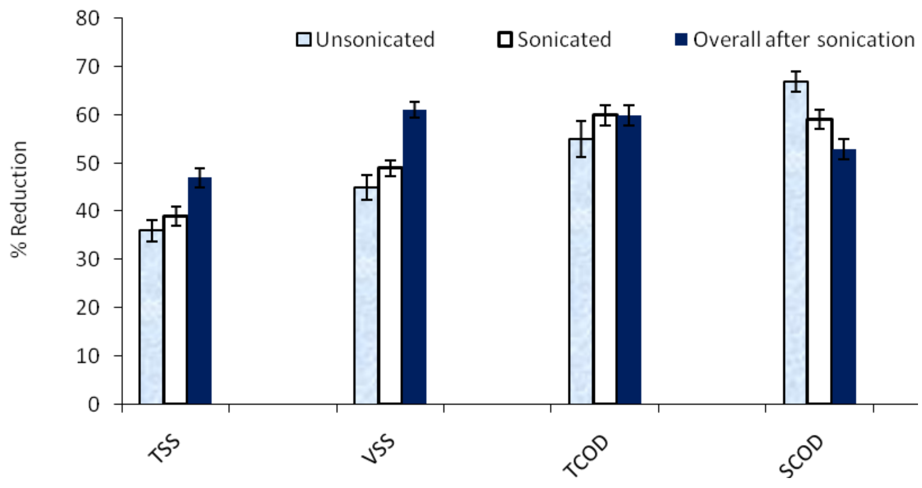
3.1. Ultrasonication of hog manure

Ultrasonication causes a localized pressure drop to below the evaporating pressure in the aqueous phase, resulting in the formation of micro bubbles by evaporation. The micro bubbles oscillate in sound field, grow by rectified diffusion and collapse in a non-linear manner. The combination of bubble oscillation and the resulting vacuum created by the collapse of the bubble leads to strong mechanical forces that can erode solid particles [23]. The hog manure was sonicated at a specific energy input of 500 kJ/kgTS. The characteristics of hog manure before and after ultrasonication are shown in Table 1. While there was no significant change in TCOD and TKN after ultrasonication, TSS, VSS, particulate protein and bound protein decreased by 17%, 21%, 10% and 12%, respectively, after sonication. Furthermore, as expected, SCOD, VFA, ammonia, soluble protein and STKN increased by 29%, 12%, 17%, 17% and 12%, respectively, after sonication. A paired t-test was conducted to evaluate the statistical significance of the observed differences as elaborated upon later.

3.2. Solids destruction

Figure 1 shows the steady-state average reductions of TSS, VSS, TCOD, and SCOD during AD for the unsonicated and sonicated manure. As shown in Figure 1, anaerobic VSS degradation efficiency of sonicated manure is higher than the unsonicated manure by 13% (51% for sonicated *versus* 45% for unsonicated). However, considering the overall VSS removal efficiency of sonicated manure both during ultrasonication and digestion into consideration, there was a 36% increase in VSS removal efficiency due to sonication, with ultrasonication/AD achieving 61% *versus* 45% reduction for AD alone. This increase of VSS removal is consistent with the findings of Nickel and Neis [24], who observed an increase in VSS degradation of sonicated waste activated sludge (WAS) by 30% at an SRT of 16 days compared to the conventional digestion. In another study, Braguglia *et al.* [25] applied ultrasonication as a pretreatment for WAS at a specific energy of 5000 kJ/kgTS, and found that the VS removal increased only from 36% to 39% at SRT of 20 days, while at SRT of 10 days, the VS removal efficiency of untreated sludge declined from 36% to 31% and for sonicated sludge from 39% to 33% *i.e.*, at both SRTs sonication affected a marginal 6–8% increase in VS destruction efficiency.

Figure 1. Degradation efficiency of unsonicated and sonicated manure.



Tiehm *et al.* [10] applied ultrasonication in a pilot plant using a high performance ultrasound reactor (3.6 kW, 31 kHz) for 64 sec on a mixture of primary sludge and WAS (53% primary sludge and 47% WAS) with average VSS of 25 g/kg, and observed a 10% increase in VS removal efficiency of sonicated waste over the conventional AD process at an SRT of 22 days, although no enhancement in VS reduction was observed at an SRT of 8 days. On the other hand, TSS removal efficiency in the digester increased from 36% to 43% with sonication, while the overall removal efficiency of TSS for sonicated manure was 47%.

3.3. COD destruction

As expected, unsonicated and sonicated manure have approximately the same influent TCOD (less than 10% difference) while the SCOD for sonicated manure was higher than of the unsonicated manure by 34% (Table 1). After digestion, there was no significant difference in TCOD removal efficiency for the sonicated and unsonicated manure. TCOD removal efficiency was 55% and 60% for unsonicated and sonicated manure, respectively (Figure 1) due to a higher soluble fraction of COD in the influent. The relatively higher TCOD removal efficiency agrees with McDermott *et al.* [26], who applied ultrasonication on aquaculture waste (consisting predominantly of fecal material and waste fish food pellets) as a pretreatment to AD and reported COD removal efficiencies of 85% and 77% for sonicated and unsonicated waste, respectively.

In our case, the SCOD concentrations deceased from 12,645 to 4188 and from 13,050 to 6147 mg /L for unsonicated and sonicated hog manure during the anaerobic digestion. The SCOD removal efficiency in the digester receiving sonicated manure was 60% *versus* 67% for unsonicated manure, attributable to the high initial SCOD resulting from ultrasonication of manure, consistent with the observation of McDermott *et al.* [26] who reported no appreciable difference in reactor effluent SCOD values between the sonicated and unsonicated waste.

3.4. Nitrogen compounds and odorous contaminants

As depicted in Figure 2, the TKN after digestion decreased by 19% and 11% for sonicated and unsonicated manure, respectively to 1450 and 1582 mg/L. STKN increased by 34% in the unsonicated manure after digestion to 1257 mg/L, while STKN in the digested sonicated manure remained constant, potentially due to higher influent STKN due to ultrasonication. Ammonia exhibited the same trend of STKN in the reactor although it was below the inhibition level (1500 mg/L) in both cases. Digested manure ammonia concentration for unsonicated manure of 1200 mg/L was higher than the 980 mg/L for digested sonicated manure.

Proteins in sludge are usually divided into three types; particulate protein, bound protein, and soluble protein [27]. The particulate protein was considered as the tightly bound protein in flocs and is composed of particles in the bacterial cell mass, and the bound protein is the labile fraction loosely attached to biomass, while the soluble protein represents protein in the solution. Bound protein is considered to be one of the main causes for odor in anaerobic digestion [28].

Figure 2. Nitrogen compounds (TKN, STKN and ammonia) concentrations for sonicated and unsonicated manure.

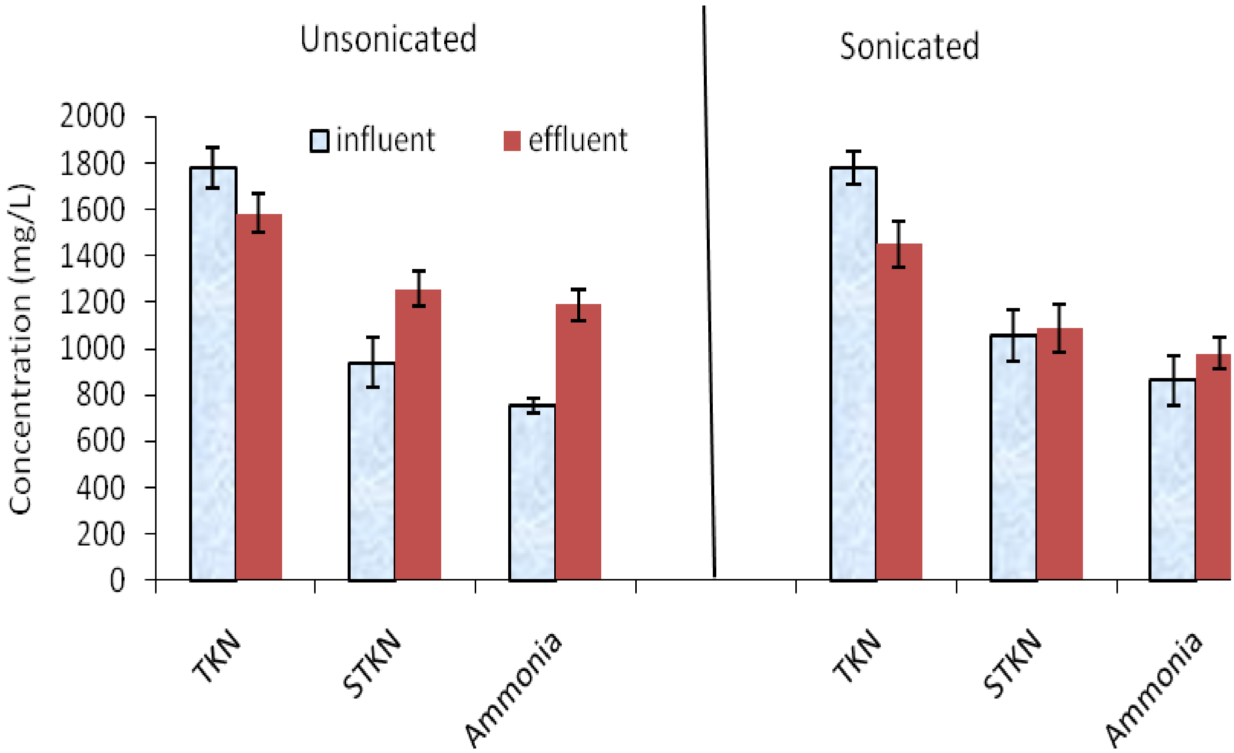
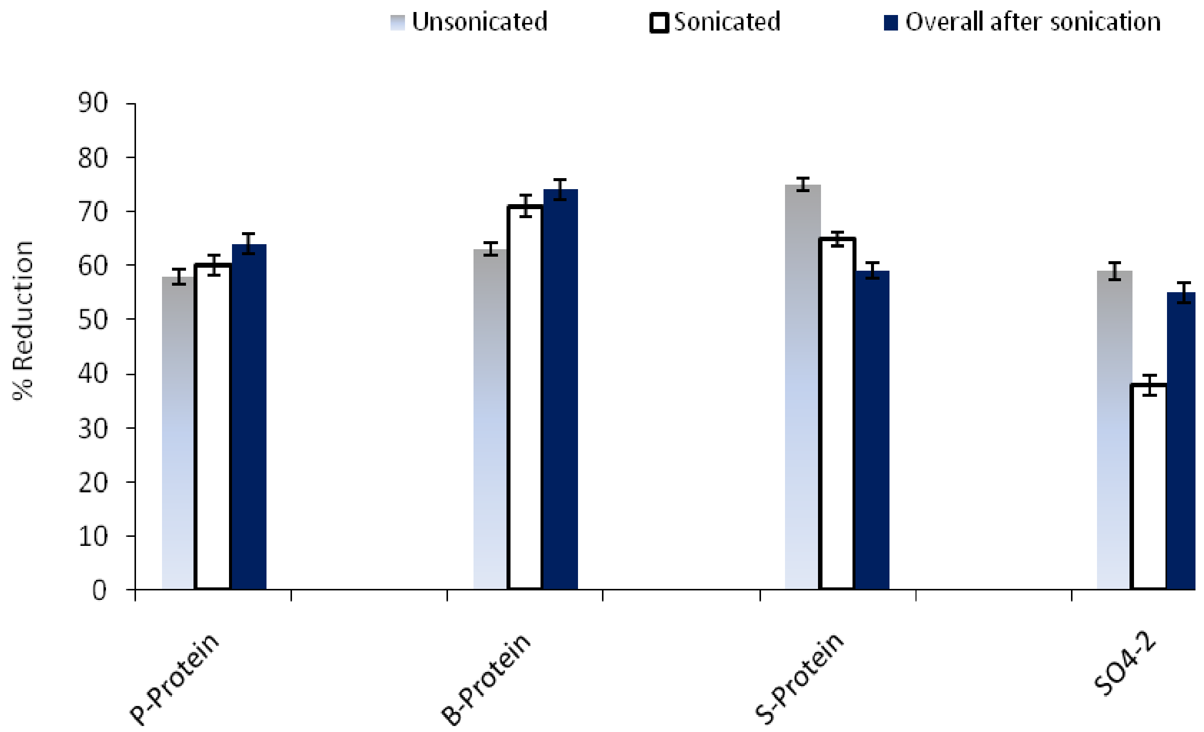


Figure 3 shows the removal efficiency of the three different types of proteins (particulate, bound and soluble) along with the sulphate reduction efficiency for the sonicated and unsonicated manure. During digestion, particulate protein removal efficiency averaged 58% and 60% for the unsonicated and sonicated manure, respectively, while the overall removal efficiency of particulate protein for the sonicated manure was 64%. The digester removal efficiency of soluble protein for unsonicated manure of 75% was higher than the 65% for sonicated manure, and the overall efficiency of soluble protein for combined sonication and digestion was 59%. This is due to the higher soluble protein concentration in the sonicated sludge due to the solubilization of the particulates. The enhancement of bound protein removal efficiency was highly discernible; a 13% increase in bound protein removal efficiency for sonicated manure during digestion relative to the unsonicated sludge, while the overall removal efficiency of bound protein for sonicated manure was higher than the unsonicated by 17.5% (Figure 2) which reflects the effect of ultrasonication on odor reduction caused by bound protein. In addition to the enhancement in bound protein reduction there was a decline in H_2S production in the digester headspace due to ultrasonication prior to digestion. The average concentration of H_2S in the headspace of the bioreactor deceased from 988 to 566 ppm for unsonicated and sonicated manure, respectively. The aforementioned reduction may reflect the effect of ultrasonication on sulfate reducing bacteria. Furthermore, SO_4^{2-} reduction during anaerobic digestion was 59% and 38% for unsonicated and sonicated manure, respectively (Figure 3).

A theoretical estimation of the headspace H_2S concentration in the biogas was conducted using observed sulfate reduction of 11.4 and 25.4 mg/L, for the sonicated and unsonicated manure with the measured values using the equation of Lens and Kuenen [29]:

$$H_2 + SO_4^{2-} \rightarrow H_2S + HS^{-} + 5H_2O + 3OH^{-} \quad (2)$$

Figure 3. Degradation efficiency of particulate protein, bound protein, soluble protein and sulfate.



Henry's constant for H_2S of 9.8 atm L/mol K at 25 °C [30] was corrected for the operating temperature of 37 °C. The calculated H_2S concentrations in both the sonicated and unsonicated manures of 494 and 954 ppm, respectively, are 13% and 4% lower than the observed 566 and 998 ppm, indicated a good mass balance in the system.

A statistical-paired t-test used to evaluate the observed differences in parameter reduction during anaerobic digestion between the sonicated and unsonicated manures, revealed that TSS, VSS, TCOD, bound protein, soluble protein and H_2S efficiencies were statistically different at the 95% confidence level with only SCOD and particulate protein insignificant at the 95% confidence level. Thus, it is evident that ultrasonication has achieved significant improvement of odor compounds (particularly bound protein and H_2S in the headspace).

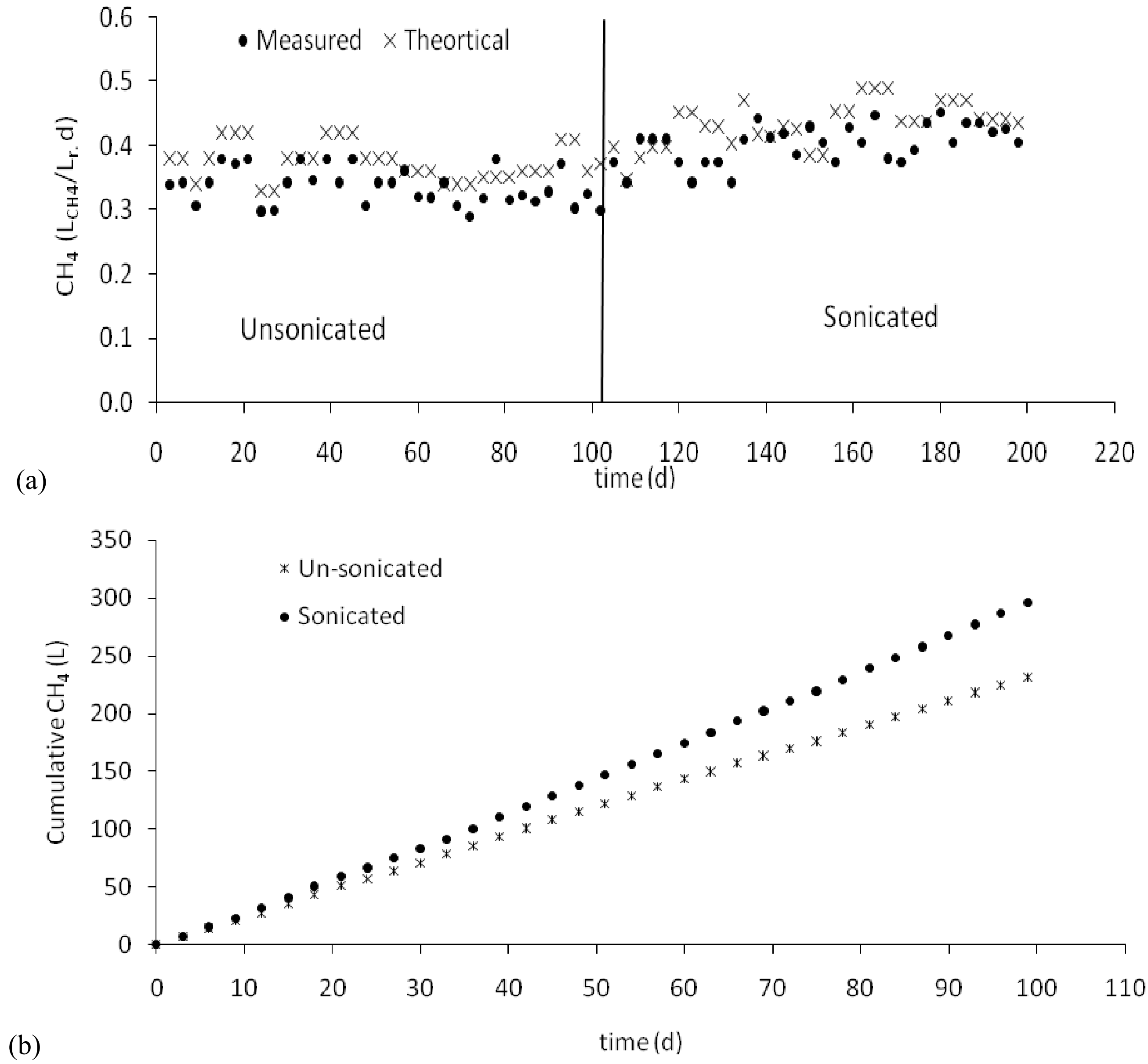
3.5. Biogas production

One of the most evident differences between sonicated and unsonicated manure was biogas production. Figure 4a shows the measured and theoretical methane (calculated as 0.4 L/g COD consumed) for the unsonicated and sonicated hog manure. As can be seen from the Figure, the methane production rate for the digester at an SRT of 15 days increased from 2.5 L/d in the unsonicated manure to 3.0 L/d for the sonicated manure, concomitant with a marginal increase in methane content from 53% to 56%. Figure 4b shows the cumulative methane production for sonicated and unsonicated manure, the maximum volumetric methane production rate increasing from 0.34 L_{CH4}/L_r.d in the unsonicated manure to 0.39 L_{CH4}/L_r.d for the sonicated manure.

3.6. BioWin model

BioWin (EnviroSim Associates, Flamborough, Ontario, Canada) was used to study the performance of anaerobic digestion of sonicated and unsonicated manures at different SRTs. The experimental data for the two runs (sonicated and unsonicated) were used to calibrate the model. Table 2 summarizes the model output for the calibration runs. As depicted in Table 2, the effluent characteristics were mostly in the range of measured average and standard deviations for both manures.

Figure 4. (a) Measured and theoretical methane production for unsonicated and sonicated hog manure. (b) Cumulative methane productions for unsonicated and sonicated hog manure.



Based on the comparison of the simulated and measured digested sludge characteristics listed in Table 2, the deviations for the unsonicated manure TSS, VSS, TCOD, SCOD, ammonia, TKN, STKN, acetic acid plus propionic acid, and daily methane production rate are 0.6%, 7.6%, 10.9%, 3.6%, 4.9%, 7.2%, 6.9%, 0.7 and 2.8%, respectively. The corresponding values for the sonicated manure are 7.9%, 6.1%, 9%, 3.5%, 22.6%, 0.2%, 14%, 19.8% and 3.3%. It is thus evident that the model default kinetic coefficients and stoichiometric parameters fit the data very well, and the effect of ultrasonication pretreatment did not change the main biochemical reactions in the anaerobic digestion significantly. Following the successful model calibration, the same influent characteristics of both raw manure and sonicated manure were used to study the effect of SRT on VSS destruction efficiency and biogas production rate. Table 3 clearly indicates that at shorter SRTs, VSS destruction efficiencies for sonicated manure were less than the unsonicated manure despite higher methane production. However, interestingly the improvement in VSS destruction efficiencies during anaerobic digestion by sonication becomes apparent at longer SRTs. At an SRT of 3 days, while the model predicts 30% more methane in digestion of sonicated manure relative to unsonicated, VSS destruction efficiencies for sonicated manure is only 60% of that for unsonicated manure. However at SRT of 30 days, a 20 % increase in methane production was projected for anaerobic digestion of sonicated manure relative to the unsonicated manure, in close agreement with the 22% increase in VSS destruction efficiencies.

3.7. Economic analysis

Table 4 shows the economic evaluation of ultrasonication pretreatment. Unit costs for dewatering and transportation, methane, and electrical energy used in the economic evaluation are $250/ton dry solids, $0.28/m^{3}CH$_4$, and $0.07/kWh. Using the specific sonication energy of 500 kJ/kgTS, the cost of sonication translates to $9.7/ton dry solids. The net benefit was calculated as the difference between the costs of methane price minus dewatering minus pretreatment (*i.e.*, sonication) for the manure. It is interesting to note that the net benefit increases sharply initially and stabilizes at $42–49/ton dry solids for SRTs of 15 to 30 days. The net benefit was most sensitive to methane production. The aforementioned discernible observation appears to be counter intuitive since logically the impact of pretreatment should have been more pronounced on heavily loaded digesters.

Table 2. Measured and simulated data using BioWin software.

Parameter (mg/L)	Unsonicated				Sonicated			
	Measured		Actual model influent	Simulated effluent	Measured		Actual model influent	Simulated effluent
	Influent	effluent			influent	effluent		
TSS	15,119 ± 552	9618 ± 687	14,642	9556	15,792 ± 680	7432 ± 409	14,402	8019
VSS	11,000 ± 526	6050 ± 414	11,640	6510	11,496 ± 510	4489 ± 768	9360	4762
TCOD	26,638 ± 1829	11,890 ± 998	26,600	13,188	28,000 ± 1540	11,284 ± 978	27,600	12,301
SCOD	12,645 ± 1238	4188 ± 507	12,396	4340	13,050 ± 1260	6147 ± 462	16,250	6360
Ammonia	753 ± 30	1187 ± 65	846	1129	824 ± 88	980 ± 100	846	1201
TKN	1779 ± 89	1582 ± 184	1779	1468	1879 ± 98	1450 ± 164	1779	1453
STKN	939 ± 108	1257 ± 176	1404	1170	939 ± 66	1088 ± 71	1517	1240
Acetic and propionic acids*	1187 ± 123	140 ± 8	1187	139	843 ± 162	172 ± 14	843	138
VSS_{dest} (%)	45 ± 2.5		44.1		51 ± 1.6		50.8	
CH_4**	2.53 ± 0.21		2.6		3.0 ± 0.26		3.1	

*Acetic and propionic acids in (mgCOD/L)

**CH_4 in (L/d)

Table 3. VSS destruction and methane production at different SRTs using BioWin software.

SRT (d)	Unsonicated manure		Sonicated manure	
	VSS destruction (%)	CH_4 (L/d)	VSS destruction (%)	CH_4 (L/d)
3	21	3.0	13.2	3.9
5	26	6.0	22	7.0
7.5	32.9	4.5	33.2	5.4
10	37.8	3.6	40.9	4.3
15	44.1	2.6	50.8	3.1
20	48	2.0	56.9	2.5
25	50.6	1.7	61.1	2.0
30	52.5	1.4	64.1	1.7

Table 4. Economical study calculation based on ton dry solids influent.

SRT (d)	Unsonicated manure				Sonicated manure				Net* $
	Energy in Dewatering		Energy out Gas		Energy in dewatering		Energy out Gas		
	wt of sludge after treatment (ton)	$ for dewatering and transportation	CH_4 (m^3)	$ from CH_4	wt of sludge after treatment (ton)	$ for dewatering and transportation	CH_4 (m^3)	$ from CH4	
3	0.87	218	80	22	0.80	199	112	31	18
5	0.83	207	267	75	0.74	186	335	94	31
7.5	0.76	191	300	84	0.68	169	383	107	36
10	0.72	180	320	90	0.63	157	411	115	39
15	0.66	165	347	97	0.57	141	445	125	42
20	0.63	156	356	100	0.53	132	467	131	46
25	0.60	150	378	106	0.50	125	482	135	44
30	0.58	146	373	105	0.48	121	492	138	49

*Net $ = [$ from CH_4 – $ for ultrasonication – $ for dewatering and transportation]$_{\text{sonicated manure}}$ – [$ from CH_4 – $ for dewatering and transportation]$_{\text{unsonicated manure}}$

Conclusions

Based on the finding of this study, the following conclusions can be drawn:

- The overall TSS and VSS removal efficiencies of sonicated manure were higher than the unsonicated manure by 36% and 31%, respectively.
- There was no significant difference in TCOD removal efficiency for the sonicated and unsonicated manure during anaerobic digestion, while the SCOD removal efficiency in the digester receiving sonicated manure was lower than that receiving the unsonicated manure.
- There was no significant difference in particulate protein removal efficiency for the sonicated and unsonicated manure in the anaerobic digester, whereas the overall removal efficiency was slightly increased (by 10%) for sonicated manure.
- The overall removal efficiency of bound protein for sonicated manure was higher than the unsonicated manure by 17.5%.
- The concentration of H_2S in the headspace of the bioreactor decreased from 988 ppm in the unsonicated manure digester to 566 ppm for sonicated manure digester, respectively.
- The effluent ammonia for digested unsonicated manure (1200 mg/L) was higher than that of sonicated manure (980 mg/L).
- The methane production rate increased from 0.34 L_{CH4}/L_r.d for the unsonicated manure to 0.39 L_{CH4}/L_r.d for the sonicated one.
- BioWin simulations indicated that at shorter SRTs, VSS destruction efficiencies for sonicated manure were less than the unsonicated manure despite higher methane production. However, interestingly the improvement in VSS destruction efficiencies during anaerobic digestion by sonication becomes apparent at SRTs around 15–30 days, which are commonly used SRTs for anaerobic digestion of biosolids in full scale.
- The net cost benefit of ultrasonication, calculated as the difference between the cost of methane output minus cost of energy input (only for ultrasonication) minus the cost of biosolids dewatering and disposal for the sonicated and unsonicated manure, increases sharply initially and stabilizes at $42–49/ton dry solids for SRTs of 15 to 30 days.

Acknowledgements

Authors want to thank Trojan Technologies, Canada and Egyptian Ministry of Higher Education for their financial contributions.

References

1. Van Velsen, A.F.M. Anaerobic digestion of swine waste. *Neth. J. Agric. Sci.* **1979**, *27*, 142–152.
2. Andreadakis, A.D. Anaerobic digestion of swine waste. *Water Sci. Technol.* **1992**, *25*, 9–16.
3. Lo, K.V.; Liao, P.H.; Gao, Y.C. Anaerobic treatment of swine wastewater using hybrid UASB reactors. *Bioresour. Technol.* **1994**, *47*, 153–157.
4. Sanchez, E.; Borja, R.; Weiland, P.; Travieso, L.; Martin, A. Effect of substrate concentration and temperature on the anaerobic digestion of piggery waste in a tropical climate. *Proc. Biochem.* **2001**, *37*, 483–489.

5. Pfeffer, J.T. Anaerobic digestion process. In Proceedings of the First Int. Symp. On Anaerobic Digestion, University College, Cardiff, Wales, UK, 1979.
6. Eastman, J.A. Ferguson J.F. Solublisation of particulate organic carbon during the acid phase of anaerobic digestion. *J. Wat. Poll. Cont. Fed*. **1981**, *53*, 352–365.
7. Parkin, G.F.; Owen, W.F. The fundamentals of anaerobic digestion of wastewater sludge. *J. Environ. Engineer*. **1986**, *112*, 867–920.
8. Wang, Q.; Noguchi, C.; Hara, Y.; Sharon, C.; Kakimoto, K.; Kato, Y. Studies on anaerobic digestion mechanism: Influence of pretreatment temperature on biodegradation of waste activated sludge. *Environ. Technol*. **1997**, *18*, 999–1008.
9. González-Fernández, C.; León-Cofreces, C.; García-Encina, P.A. Different pretreatments for increasing the anaerobic biodegradability in swine manure. *Bioresour. Technol*. **2008**, *99*, 8710–8714.
10. Tiehm, A.; Nickel, K.; Nies, U. The use of ultrasound to accelerate the anaerobic digestion of sewage sludge. *Water Sci. Technol*. **1997**, *36*, 121–128.
11. Wang, Q.; Kuninobu, M.; Kakimoto, K.; Ogawa, H.I.; Kato, Y. Upgrading of anaerobic digestion of waste activated biosolid by ultrasonic pretreatment. *Bioresour. Technol*. **1999**, *68*, 309–313.
12. Tiehm, A.; Nickel, K.; Zellhorn, M.; Neis, U. Ultrasonic waste activated biosolid disintegration for improving anaerobic stabilization. *Water Res*. **2001**, *35*, 2003–2009.
13. Neyens, E.; Baeyens, J.; Dewil, R.; De Heyder, B. Advanced biosolid treatment affects extracellular polymeric substances to improve activated biosolid dewatering. *J. Hazard. Mater.* **2004**, *106*, 83–92.
14. Lawler, D.F.; Chung, Y.J.; Hwang, S.J.; Hull, B.A. Anaerobic digestion: Effects on particle size and dewaterability. *J. Water Pollut. Control Fed*. **1986**, *58*, 1107–1117.
15. Quarmby, J.; Scott, J.R.; Mason, A.K.; Davies, G.; Parsons, S.A. The application of ultrasound as a pretreatment for anaerobic digestion. *Environ. Technol.* **1999**, *20*, 1155–1161.
16. Pérez-Elvira, S.I.; Nieto-Diez, P.; Fdz-Polanco, F. Sludge minimisation technologies. *Review Environ. Sci. Bio-Technol*. **2006**, *5*, 375–398.
17. Stukey, D.C.; McCarthy, P.L. Thermochemical pretreatment of nitrogenous materials to increase methane yield. *Biotechnol. Bioeng. Symp.* **1978**, *8*, 219–233.
18. Lens, P.; Visser, A.; Janssen, A.; Pol, L.; Lettinga, G. Biotechnological treatment of sulfate-rich wastewaters. *Critic. Review Environ. Sci. Technol*. **1998**, *28*, 41–88.
19. APHA, *Standard Methods for the Examination of Water and Wastewater*, 20th Edition; American Public Health Association: Washington DC, USA, 1998.
20. Speece, R.E., *Anaerobic Biotechnology for Industrial Waste Waters*; Archae Press: Nashville, TN, USA, 1996.
21. Lowry, O.H.; Rosebrough, N.J.; Farr, A.L.; Randall, R.J. Protein measurements with the folin phenol reagent. *J. Biol. Chem*. **1951**, *193*, 265–275.
22. Bougrier, C.; Carrère, H.; Delgenès, J.P. Solubilisation of waste-activated sludge by ultrasonic treatment. *Chem. Eng. J.* **2005**, *106*, 163–169.
23. Tiehm, A.; Nickel, K.; Nies, U. The use of ultrasound to accelerate the anaerobic digestion of sewage sludge. *Water Sci. Technol.* **1997**, *36*, 121–128.

24. Nickel, K.; Neis, U. Ultrasonic disintegration of biosolids for improved biodegradation. *Ultrason. Sonochem.* **2007**, *14*, 450–455.
25. Braguglia, C.M.; Mininni, G.; Gianico, A. Is sonication effective to improve biogas production and solids reduction in excess sludge digestion? *Water sci. Technol.* **2008**, *57*, 479–483.
26. McDermott, B.L.; Chalmer, A.D.; Goodwin, J.A. Ultrasonication as a pre-treatment method for the enhancement of the psychrophilic anaerobic digestion of aquaculture effluents. *Environ. Technol.* **2001**, *22*, 823–830.
27. Dimock, R.; Morgenroth, E. The influence of particle size on microbial hydrolysis of protein particles in activated sludge. *Water Res.* **2006**, *40*, 2064–2074.
28. Higgins, M.; Glindemann, D.; Novak, J.T.; Murthy, S.N.; Gerwin, S.; Forbes, R. Standardized biosolid incubation, headspace odor measurement and odor production consumption cycles. In Proceedings of the Water Env. Federation and AWWA Odors and Air Emissions Conference, Bellevue, Washington, April 2004.
29. Lens, P.N.L.; Kuenen, J.G. The biological sulfur cycle: New opportunities for environmental biotechnology. *Water Sci. Technol.* **2001**, *44*, 57–66.
30. Stumm, W.; Morgan, J.J. *Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters*, 2nd Edition; John Wiley & Sons: New York, NY, USA, 1981.