Research Article

Sound enhances wastewater degradation and improves anaerobic digester performance

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Abstract

Biogas production and wastewater quality from anaerobic digesters were studied to determine whether sound at sonic frequencies (< 20,000 Hz) could enhance their performance. In three trials with increasing waste loading rates, each of 100-day duration, the performance of control and sound-treated digesters was compared. Anaerobic digesters exposed to sound produced approximately 12% more biogas than did non-exposed digesters, and sound-treated digestate had significantly lower chemical oxygen demand. Sludge at the end of the 100-day digestion averaged 19% less carbon and 18% less nitrogen in sound-treated digesters as compared to sludge from untreated digesters. Although the mechanism(s) responsible for enhanced biogas production due to sound exposure are unknown, recordings of sound-treated digesters indicate that acoustically induced cavitation may play a role.

Keywords Acoustic cavitation · Acoustics · Anaerobic digestion · Biogas · Cavitation · Carbon dioxide · Methane

1 Introduction

In 2016, over 80% of energy in the USA was generated by fossil fuels. Of the rest, only about 10% was generated by renewable resources, and only about 5% of this renewable energy was produced by utilization of biomass waste [1]. There are numerous adverse environmental impacts caused by this underutilization. The waste may be treated, as in sewage treatment plants, which have elaborate infrastructure requirements and require large energy inputs [2], landfilled, which uses valuable land and may cause air, soil and water pollution [3], or it may simply remain untreated.

The European Union has made a commitment to the increased use of renewable energy sources to enhance energy independence and meet requirements of the Kyoto Protocol (Directive 2009/28/EC of the European Parliament). Increased production of biogas is an integral part of this commitment, which states in part that "The use of agricultural material such as manure, slurry and other animal and organic waste for biogas production has, in view of the high greenhouse gas emission saving potential, significant environmental advantages in terms of heat and power production" [4].

Thus, there is great environmental and legislative pressure to utilize biomass for energy production. The use of biomass waste rather than cultivated biomass enhances the environmental and economic benefits that can be realized. Rather than dedicating land and resources such as water and energy to produce biomass, waste products such as crop residuals and manure may be exploited to maximize environmental benefits.

In the USA, there is great potential for energy production from biomass waste. In addition to degradable municipal solid waste, food and food processing waste,

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as well as agricultural residuals, over one billion tons of animal manure is estimated to be produced annually [5]. If only a small percentage of this manure was used as feedstock for the generation of biogas, significant revenue could be generated along with appreciable environmental benefits.

However, while anaerobic digestion of animal, food and other wastes to produce biogas is an attractive option for the generation of renewable energy, a few technical and economic difficulties have limited its mainstream acceptance. The anaerobic digestion of wastewater takes place slowly, necessitating a blend of long hydraulic retention times (HRT), elevated operating temperatures and mechanical mixing resulting in trade-offs between gas production and wastewater treatment efficiency as well as capital construction and operational costs. Long HRT, for instance, results in larger capital costs, and overly long HRT results in higher operational costs relative to the gains achieved in biogas yields [6]. Given the high heat capacity of water, higher operating temperatures result in significant costs due to fuel consumption along with costs due to installation and maintenance of heaters. Mixing of digestate involves installation of expensive and high maintenance equipment and does not always improve gas production or wastewater treatment [7].

Innovative technologies are being developed to improve the efficiency of anaerobic digestion. Combining heat and free ammonia to disrupt the extracellular matrix of waste-activated sludge, for instance, significantly increases the waste hydrolysis rate and methane production [8]. Treatment of polyacrylamide-flocculated solids at high pH also increases hydrolysis rate and methane production [9]. Engineering iron oxide particles for slow release has also been shown to improve biogas production significantly [10].

The use of sound to stimulate waste degradation also has the potential to address some of the limitations of anaerobic digestion. For instance, sound at sonic or audio frequencies (< 20,000 Hz) can enhance growth of bacteria such as *Brevibacillus parabrevis* and *Escherichia coli* and yeast such as *Saccharomyces cerevisiae* [11–13]. The mechanism(s) responsible for these observations have not been elucidated but could involve activation of piezo-channels and thereby enhance ion uptake [14]. It is also possible that cavitation from applied acoustic pressure enhances nutrient exchange as bubbles oscillate and collapse with the ensuing microscopic reentry jets resulting in enhanced movement of water. For a treatment of cavitation, see Brennen [15]. Acoustic streaming, wherein flow is induced within a fluid by absorption of sound [16, 17], could also play a role by enhancing nutrient exchange as could vibrational energy imparted to bacteria and wastewater particles in response to acoustic pressure.

Regardless of the mechanism(s) responsible for the observed enhancement of microbial growth, it seemed reasonable to investigate whether sound could be used to enhance biogas production from anaerobic digesters. Accordingly, we conducted these experiments in which the performance of anaerobic digesters was studied with and without audio treatment.

2 Materials and methods

2.1 Digester design

Two digesters were constructed from 1040-L (275-gallon as sold) blow-molded intermediate bulk container (IBC) tanks with a length of 1.2-m, width of 1.0-m and height of 1.15-m. The top of each tank had a hole drilled into it to accommodate 1.27-cm-diameter cross-linked polyethylene (PEX) tubing fitted with a manual ball valve that served as the feed inlet. This pipe extended into the tank below the surface of the digestate liquid. Float level switches (Omega Engineering Inc., Norwalk, CT) were installed in the side of the tanks to maintain a digestate volume of 800-L. The float level switch was used to activate an electrical relay (American Zettler, Inc., Aliso Viejo, CA) routing power to a 1.27-cm full port solenoid-actuated 120-VAC PVC ball valve (Valworx, Inc., Cornelius, NC) installed on 1.27-cm-diameter PVC pipe placed 44 cm above the tank bottom that served as the waste outlet.

The top of each IBC tank was adapted to accommodate a 3-way luer valve and 6.35-mm tubing that served as a gas outlet and sampling port. The tubing was connected to a Wet Tip Flow Meter® (wettipgasmeter.com) by one arm of a three-way luer valve fitting. The other arm of the fitting accommodated a syringe for taking samples for gas analysis. The side of the tank had an addition of 0.635-cm-diameter port with two-way luer valve installed 34 cm above the tank bottom for liquid analysis. All pipe and tubing connections to the tanks were made with Uniseal® pipe to tank fittings (US Plastic, Inc.).

2.2 Digester operation

Swine waste was obtained from a waste lagoon of a farrow to finish operation located in north-central Kentucky. Initially, 1000-L of swine waste was pumped into each tank which activated the float switch-controlled waste outlet as a means of partially concentrating wastewater solids and attaining the operating wastewater volume of 800 L.

The experiments were conducted in duplicate as three separate trials of 100-day duration. In the first trial, the digesters were fed 290 g of a two-part ground corn to one-part defatted soybean meal in 57 L of water twice weekly for a total of 8.41 kg, in the second trial, the digesters were fed 565-g corn twice or three times weekly for a total of 23.84 kg and in the third trial, the digesters were fed 700-g corn meal, later increased to 1 kg of corn meal twice or three times weekly for a total of 62.5 kg.

Gas production was measured daily during the workweek and averaged over the weekends. Gas and wastewater quality was measured weekly as described in Loughrin et al. [18].

2.3 Sound experiments

MP3 files were created from WAV files constructed using NCH Tone Generator software ver. 3.07 (NCH Software, Greenwood Village CO). The WAV files consisted of single or multiple (two-eight)-frequency harmonic sine waves ranging from 20 to 20,000 Hz. The sound files consisted of either simple sine waves at constant frequencies or were modified by conducting frequency sweeps. The WAV files were converted to MP3 format using Wavepad software ver. 5.96 (NCH Software) either unmodified or with application of 6-Hz tremolo to afford a rapid variation in amplitude. These files were played to the digesters at two-thirds of volume for 3 h with 1 h breaks throughout the day in the beginning of the first trial of the digesters. As discussed in more detail later in the paper, based on harmonics observed from bubbles resonating in response to exposure to sine waves at constant frequencies, the frequency sweeps and tremolo-modified sound files were replaced with sound files consisting of a single 1000-Hz sine wave or simultaneous 1000- and 5000-Hz sine waves.

Recording was performed using a DolphinEar DE200 hydrophone (www.dolphinear.com) interfaced to a computer using Audacity ver. 2.0.6 recording software (www.audacityteam.org). Recordings were saved as 16-bit MP3 files with a bit rate of 192-kbps.

Amplification was supplied by a Pyle PTAU45 amplifier rated at 20-W RMS (root-mean-square) power at one kHz (Pyle Audio, Inc., Brooklyn NY) with USB memory drive input. Actual power consumption was measured with an Intertek power meter (Intertek Group PLC, London, UK) using a 1 kHz sine wave. During playback of sounds to the digester, the amplifier was set to three-quarters volume.

In the first trial, sound was provided by an Aquasonic Model AQ339 underwater speaker (Clark Synthesis Inc., Highlands Ranch, CO). The speaker was placed on the bottom center of the tank. The second trial was conducted in the same manner until day 71 when the speaker failed. After this, sound was supplied to the digester by two Skar FSX65 150-W RMS speakers (Skar Audio Inc., Tampa FL) placed near the bottom outside of the tank. In the third trial, the same speakers were rendered waterproof by coating them with GE Silicone I sealant (General Electric Corp., Boston MA). The speakers were placed in corners of the tank along the same side.

Examples of MP3 sound files played to the digesters and recordings of digesters exposed to the sound files can be found in the supplemental material.

2.4 Chemical analyses

All analyses were performed weekly prior to feeding of the digesters as described previously [18, 19]. Briefly, biogas and dissolved gases (solvated CO_2, bicarbonate) were analyzed by injection of 1.0-mL samples onto a Varian Model CP-3800 (Agilent Technologies, Santa Clara, CA) gas chromatograph (GC) modified for greenhouse gas (GHG) analysis by RSC Group LLC (Katy, TX) while hydrogen sulfide and sulfide were analyzed by injection of 1.0-mL samples onto a SRI Instruments 8610c GC equipped with a flame photometric detector (SRI Instruments, Torrance, CA). Twenty-mL samples of biogas were collected at a 3-way luer valve and 0.635-cm tubing that served as a gas outlet and sampling port. The tubing was connected to a Wet Tip Flow Meter® (wettipgasmeter.com) by one arm of a three-way luer valve fitting. The other arm of the fitting accommodated a syringe for taking samples for gas analysis. The side of the tank had an additional 0.635-cm-diameter port installed for liquid analysis. One-half mL of samples was injected into a capped 20-mL vial containing 9.5 mL of 0.1 M HCl.

Chemical oxygen demand (COD) and total suspended solids (TSS) were performed by standard methods [20], and ion chromatography was performed on samples passed through 0.2-μm filters and analyzed on a Dionex ICS 3000 ion chromatograph (Dionex Corp., San Francisco, Cal.).

Statistical analyses were performed using SAS ver. 9.2 (SAS Institute, Cary, NC) with data comparisons performed using PROC ANOVA and descriptive statistics calculated using PROC MEANS.

3 Results and discussion

3.1 Spectral analysis of sound-excited digestate

As stated, in the beginning of trial 1 of the digesters, a variety of audio files were played to the digesters. These files consisted of either single-frequency sine waves (20, 300, or 1000 Hz) or multiple sine waves consisting of up to eight harmonic tones (e.g., 300, 600, 900… 2400 Hz) or linear sweeps from 20 to 20,000 Hz over 5 min. The linear sweeps were either unmodified or altered by the application of a 6-Hz tremolo, that is, a rapid modulation of the signal amplitude. The rationale for employing these sound files was that a multiplicity of bubbles exist in the digestate with fluctuating radii that have corresponding resonant frequencies. Therefore, varying the frequency and amplitude of the sound files might excite the widest range of bubbles leading to their growth and eventual collapse.

Early on, however, it was found that exposing the digestate to single-frequency sine waves was most effective in affecting bubble resonance and thereby the energy status of the digestate. Figure 1 illustrates this phenomenon. It shows an original 1000-Hz signal played to the digester,

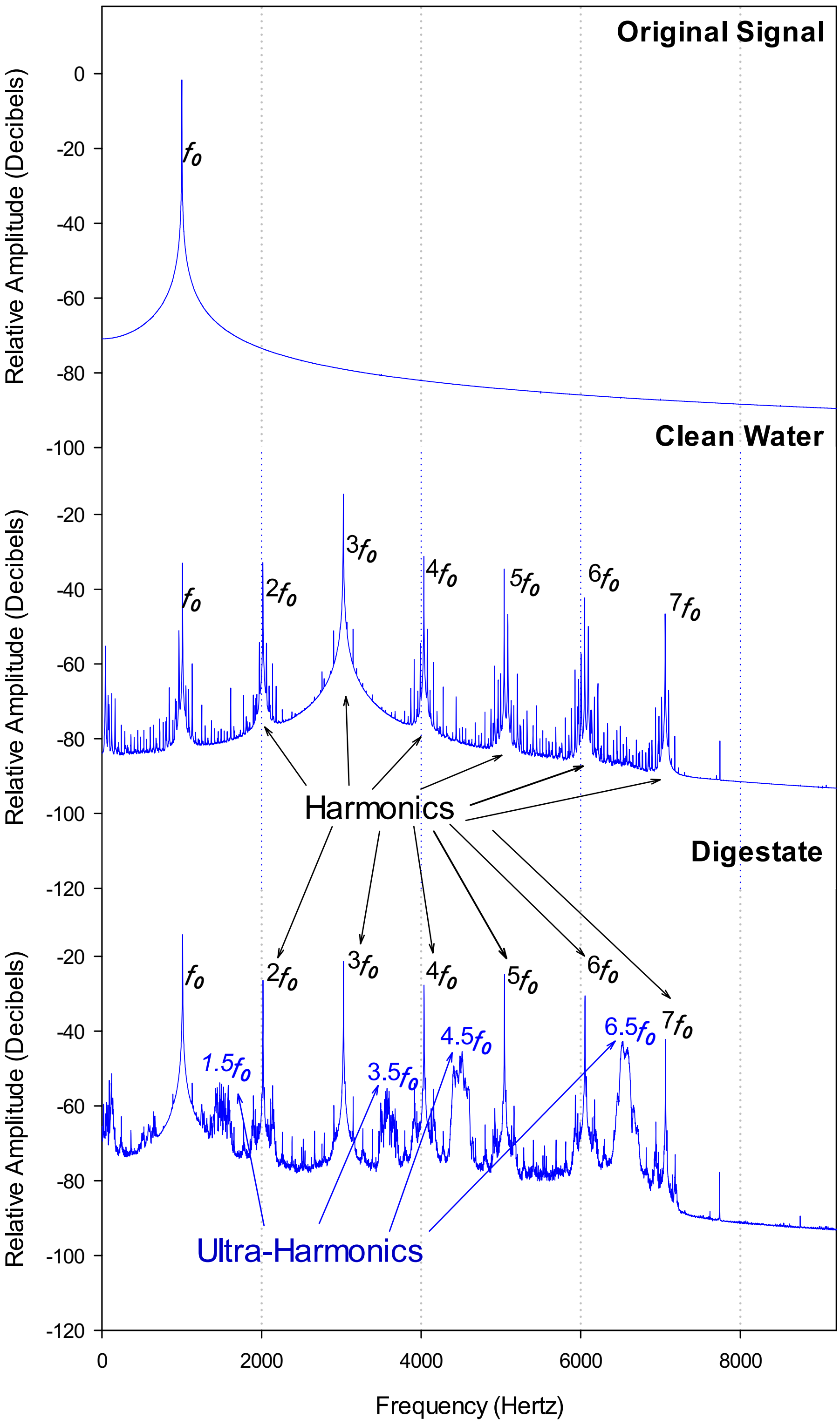

Fig. 1 One-thousand-hertz sine wave as original signal, as played in clean, non-degassed waster and played in digestate

the signal in relatively clean, non-degassed water and in digestate. In clean water, peaks at the fundamental frequency f_0 and two, three, four, five, six and seven times f_0 were prominent. These peaks are due to nonlinear oscillations of the bubbles indicative of "stable" or non-inertial cavitation, or in other words, oscillations of the bubbles in response to the applied acoustic pressure [21]. Although deemed stable cavitation, bubbles oscillating in response to an acoustic field grow as their radii increase and internal pressure decreases leading to dissolved gas influx from the liquid phase. Therefore, bubbles undergoing non-inertial cavitation tend to grow until their radii reach a critical value and bursting occurs due to low internal vapor pressure [17].

When the digestate was exposed to single-frequency sine waves, f_0 and its harmonics were again prominent. At irregular intervals, however, broad ultra-harmonic peaks would appear, usually first at 3.5 times f_0, but later also at 1.5, 2.5 and 4.5 times f_0. This is indicative of incipient inertial cavitation (bubble collapse) and would often devolve into broadband noise revealing widespread inertial cavitation. This broadband noise was of long duration and often persisted long after the audio stimulus was stopped, in some cases for as long as 30 min.

Figure 2 shows the audio spectrum of anaerobic digestate prior to, and approximately 4 min after cessation of a 20-min exposure to simultaneous 1000- and 5000-Hz sine waves. In this instance, as described, after appearance of ultra-harmonic peaks the more stable oscillations of the bubbles undergoing non-inertial oscillations became more chaotic as the bubbles were forced to undergo nonlinear oscillations. The resulting broadband noise from these oscillations and inertial collapse of bubbles within the digester could represent a significant input of energy into the digestate, a means of mixing/agitation within the digester, and thereby a method of particulate matter breakdown. The study of cavitation inception and dynamics is complex. For in-depth treatment of some of these issues, the reader is directed to Brennen [15].

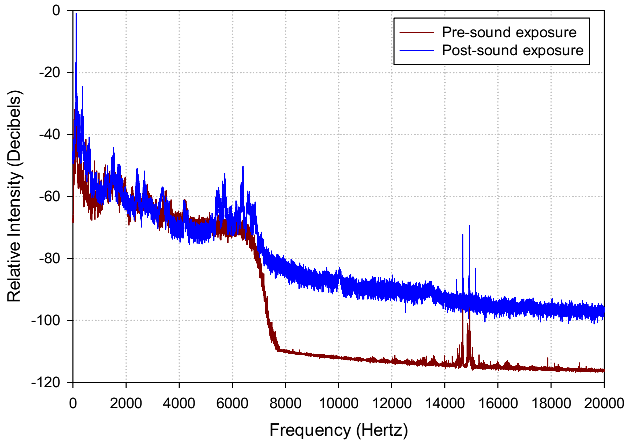

Fig. 2 Audio spectrum of anaerobic digestate prior to and 5 min after exposure to mixed 1000 and 5000 Hz sine waves

3.2 Effect of sound excitation on biogas production

We were able to expose the digestate to sound for prolonged periods and able to demonstrate that under certain conditions that chaotic cavitation could be induced signifying increased energy input into the digesters. The possible consequences of this in terms of biogas production are presented in Table 1. Digesters exposed to audio produced significantly more biogas than did control digesters (Analysis of Variance, $F(1,200)=5.13$, $p=0.0239$). The composition of the biogas was similar in sound-treated and control digesters. However, the concentration of CO_2 was approximately 9% higher and CH_4 5% higher in sound-treated digesters than in control digesters. Hydrogen sulfide concentrations were approximately 8% higher in control than in sound-treated digesters.

Although audio-treated digestate did produce biogas with higher concentrations of CO_2 and CH_4, this was not likely due to degassing of the digestate since dissolved gas concentrations were similar in both treated and untreated digestate. This being stated, solvated CO_2 and CH_4 were 2 and 1.1 mM lower in sound-treated digestate than in control digestate. The solvated CO_2, however, was likely lower in the sound-treated digestate due to higher pH (Table 2) resulting in shifting the equilibrium between the two

Table 1 Gas analyses from control digesters and digesters exposed to sound

Parameter	Treatment	
	Untreated	Sound
Daily gas production (L^{-1})[a]	147 ± 8.5	164 ± 8.6*
Concentration in biogas (mM)[b]		
Carbon dioxide	14,600 ± 786	15,900 ± 618
Methane	18,300 ± 1280	19,200 ± 1050
Hydrogen sulfide	220 ± 32.0	204 ± 27.6
Concentration in wastewater (mM)		
Bicarbonate	56.9 ± 7.10	59.5 ± 6.57
Solvated carbon dioxide	11.6 ± 0.83	9.61 ± 0.64
Solvated methane	29.3 ± 3.62	28.2 ± 1.16
Bisulfide	2.77 ± 0.87	3.70 ± 1.75
Solvated hydrogen sulfide	1.83 ± 0.56	2.26 ± 0.86

*Significant difference in means ($P > 0.05$) by PROC ANOVA

[a] Data represent the mean ± standard error of the mean of 100 determinations from each of three trials

[b] Data represent the mean ± standard error of the mean of 14 determinations from each of three trials

Table 2 Wastewater analyses from control digesters and digesters exposed to sound

	Treatment	
	Untreated	Sound
pH[a]	6.83 ± 0.12	7.05 ± 0.10
Concentration (mg L^{-1})		
Chemical oxygen demand[b]	2290 ± 237*	2060 ± 240
Total suspended solids[b]	1250 ± 191	1110 ± 188
Ammonium[c]	100 ± 14.4	98.8 ± 20.2
Sodium[c]	87.2 ± 10.4	91.5 ± 10.2
Potassium[c]	199 ± 23.5	204 ± 20.2
Calcium[c]	55.3 ± 3.76	57.0 ± 3.03
Orthophosphate[c]	23.8 ± 2.57	29.0 ± 3.38
Sulfate[c]	0.38 ± 0.12	0.43 ± 0.13

*Significant difference in means ($P > 0.05$) by PROC ANOVA

[a] Data represent the mean ± standard error of the mean of 14 determinations from each of three trials

[b] $n = 11$ determinations from each of three trials

[c] $n =$ seven determinations from each of three trials

species toward bicarbonate. Similarly, bisulfide (HS^-) was higher in the sound-treated digestate although solvated H_2S was also higher in the sound-treated digesters.

3.3 Effect of sound excitation on biogas production

Wastewater quality, however, was improved in the sound-treated digesters as compared to untreated digesters (Table 2). Chemical oxygen demand was 11.1% higher in control digesters than in sound-treated digesters (Analysis of Variance, $F(1,26) = 3.96$, $p = 0.051$) while total suspended solids were 12.6% higher in control digesters (Analysis of Variance, $F(1,26) = 5.81$, $p = 0.0239$).

Other indicators of wastewater quality such as ammonium and other ions were similar in the two treatments. Still, TSS were lower in the sound-treated digesters while orthophosphate was somewhat higher. Both findings could indicate enhanced degradation of the waste due to vibrational energy imparted to wastewater particles and cavitationally induced breakdown of sludge particles. In the case of orthophosphate, this would be due to increased degradation of sludge and freeing of the phosphate from organically bound forms such as phytic acid.

We did notice that sludge removed from the digesters treated with audio appeared more degraded than that from untreated digesters. Figure 3 shows sludge removed from the digesters at the end of trial 3. Sludge from the untreated digestate was lighter in color and had larger pieces of corn remaining than did audio-treated sludge. At the end of this trial, sludge from the audio-treated digestate averaged 7800- and 1800-µg g^{-1} carbon and nitrogen, respectively, whereas sludge from the untreated digestate averaged 19,000- and 1800-µg g^{-1} carbon and nitrogen, respectively. Overall, for the three trials, sludge from audio-treated digestate averaged 19% less carbon and 18% less nitrogen than did sludge from untreated digestate.

Fig. 3 Sludge samples removed from digesters at the end of trial three. Left, sludge removed from sound-treated digester, right, sludge sample removed from control digester

Enhanced sludge breakdown led to greater biogas production in the loudspeaker-equipped digesters. As discussed, this could be due to several factors, the relative contribution of each being uncertain. The only evidence we obtained for involvement of any of these factors, though, was the broadband noise indicative of widespread cavitation within the digestate. In non-inertial cavitation, in which bubbles oscillate in an acoustical field, the resonant frequencies of a given bubble are proportional to its radius [15]. Therefore, bubbles resonating at sonic frequencies are much larger than those which resonate at ultrasonic (> 20,000 Hz) frequencies.

Hydrodynamic cavitation has been used to enhance the breakdown of waste-activated sludge and distillery wastewater and thereby improve biogas production [22, 23]. Padoley et al. [22], for instance, were able to reduce the COD of a distillery wastewater by 70% while increasing biogas production almost 12-fold. In hydrodynamic cavitation, bubbles form in regions of reduced pressure; for example, as occur in flowing liquids at the outlets of constricted flows or as caused by impellers and propellers. The bubbles may then implode violently as they travel away from the regions of reduced pressure, providing their internal pressures are below the local saturated vapor pressure of the liquid. Although intense pressures can be generated as the bubbles collapse, this phenomenon is more localized and energy consuming than acoustic cavitation. Furthermore, acoustic energy may travel great distances in water depending on the frequency of the sound and subject to attenuation by suspended matter and/or bubbles [24, 25]. In Padoley et al. [22], hydrodynamic cavitation was induced by pumping distillery wastewater through a venturi using a positive-displacement pump rated at 1.1 kW. In the present experiment, the amplifier output was rated at 20-W RMS and consumed 34.2 W when playing a 1000-Hz sine wave at three-quarters volume.

There may have been a tendency for the sound to be attenuated by suspended particles in the digesters, thereby limiting its effectiveness. In the first trial, gas production was low, averaging only 3.97 L kg^{-1} of feed. Gas production in the sound-treated digester was 2.6-fold higher from the sound-treated digester than from the control digester. In the second trial, gas production at 561 L kg^{-1} feed was 8.5% higher than that of the control digester. In the third trial, gas production from the sound-treated digester was 526 L kg^{-1} feed, 4% higher than that of the control digester. Average TSS solids for trials 1, 2 and 3 were 168, 465, and 2060 mg L^{-1}, respectively. The higher TSS could act to limit the effectiveness of sound in treating the wastewater, both directly and by acting as nucleation sites for gas. This could perhaps be addressed by suspending the speakers above the sludge layer, rather than within it as was done in these experiments, thereby reducing sound attenuation.

Cavitation induced by ultrasound has been exploited to break down kidney stones and for critical cleaning purposes. Cavitation induced at ultrasonic frequencies differs from that induced at sonic frequencies in that the energy released is much greater. This can be inferred from the fact that internal gas pressures are much greater in small bubbles than in large ones and that much higher surface tensions are required to stabilize the small bubbles that have resonant frequencies in the ultrasonic range.

Nevertheless, sonically induced cavitation may have the capability of accelerating sludge breakdown and thereby improving biogas production. It is also not difficult to envision that collapsing bubbles induce significant water flows that may aid in nutrient exchange within the sludge.

4 Conclusions

While cavitation is usually viewed as an undesirable phenomenon, causing wear to equipment such as impellers and valves, it is clear from these results that when cavitation is properly managed, it may be used to improve gas production from anaerobic digestion, or viewed from another perspective, speed up the rate of digestion. This result is most noteworthy in that potentially relatively little energy input is required to achieve significant enhancement in anaerobic digester performance.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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