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High Rate Manure Slurry Anaerobic Digestion

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Abstract

The study shows that high rate anaerobic digestion may be an efficient way to obtain sustainable energy recovery from slurries such as pig manure. High process capacity and robustness to 5 % daily load increases are observed in the sludge bed reactors investigated. Settled, stored pig manure was fed at rates giving hydraulic retention times, HRT, gradually decreased from 42 to 1.7 hours imposing a maximum organic load of 400 g COD L^{-1} reactor d^{-1}. The reactors reached a biogas production rate of 97 g COD L^{-1} reactor d^{-1} at the highest load at which process stress signs were apparent. The yield was ~0.47 g COD methane g^{-1} COD_T feed at HRT above 17 h, gradually decreasing to 0.24 at the lowest HRT. Reactor pH was stable at 8.0 ± 0.1 at all HRTs with alkalinity between 9-11 g L^{-1}. The first stress symptom occurred as reduced methane yield when HRT dropped below 17 h. When HRT dropped below 4 h the propionate removal stopped, implying that propionate degradation was rate limiting, explained by growth kinetics inhibition. The yield from acetate removal was constant at 0.17 g COD acetate removed per g COD_T substrate. This robust methanogenesis implies that pig manure, and probably other similar slurries, can be digested for methane production in compact and effective sludge bed reactors. The relatively fast adaptation to manure for microbial communities implies that non-adapted sludge can be used to start the sludge bed bioreactors.

Keywords: Gravity settled pig manure; Energy from slurries; AD stability; High organic load; Microbial communities

1. Introduction

Governments promote anaerobic digestion (AD) of manure because it can reduce greenhouse gas (GHG) emissions and odors, produce renewable energy as methane and improve fertilizer properties (Masse et al., 2011). The largest potential source of methane by anaerobic digestion (AD) of wet organic waste is manure, e.g. ~40 % in Norway, but an insignificant fraction of this is realized (Berglann and Krokann, 2011). The main reason for this is the low energy density of manure, implying low production rates in continuous flow stirred tank reactors (CSTR) currently used for manure AD. Such solutions are not sustainable because the costs of construction and operation of such plants are larger than the value of the methane produced (Berglann and Krokann, 2011). Large scale farms may have their own CSTR AD solutions that are economically sustainable (Raven and Gregersen, 2007) but agriculture is dominated by smaller farms where such systems may not be rentable. Manure transport to central AD treatment plants is used to some extent, especially in Germany, but the sustainability of such solutions is questioned due to transport cost of manure with low biogas potential.

More efficient process solutions for AD treatment of manure are therefore required. High rate AD reactors may treat waste in smaller and presumably much cheaper digesters. A high rate AD manure treatment technology that is well integrated with existing farm infrastructure for slurry based manure handling systems, common for cattle and pig farms (Burton and Turner, 2003), is therefore investigated here. Manure from farms using slurry based handling systems has 61 % of the total theoretical Norwegian manure energy potential of 2480 GWh/a (Raadal et al., 2008). The situation vary some around the world but it is assumed that the case investigated here is relevant for a large fraction of modern global agriculture, as well as aquaculture and other activities producing organic waste slurries.

Manure storage tanks with 8 months minimum HRT capacity, already installed in cold climate countries (e.g. Norway, to comply with government regulations to avoid use as fertilizer outside the short growth season), may serve as a first step in an AD treatment line and/or be used for effluent storage. It has been observed that manure particles disintegrate and hydrolyze during such storage, thereby improving its quality as AD feed (King et al., 2011; Bergland et al.,2014). In such tanks manure separates spontaneously into a floating layer (straw, wood chips, etc.), a bottom sediment layer and a middle layer with much less suspended solids than the floating and bottom layers (Fig. 1). Potentially suitable high rate AD feed can be taken out from the middle layer at no extra cost. A main issue of the present study is to determine if this middle layer can be used as feed for high rate AD. The assumption is that, if a sludge blanket high rate AD works well on such feed, this process can become economically feasible.

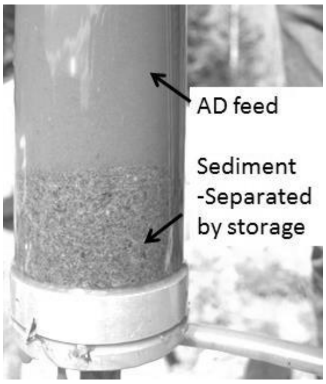

Figure 1. Pig manure sample collected near the bottom of a pig manure storage tank.

The original and most extensively used high rate reactor is the UASB (upflow anaerobic sludge blanket), developed by Lettinga et al. (1980). Such sludge blanket reactors are used to treat the liquid fraction of organic waste containing small amounts of suspended solids (Tchobanoglous et al, 2003). The particle content of settled manure (Fig. 1) is higher (> 6 g TSS L^{-1}) than recommended for UASB treatment (Tchobanoglous et al., 2003). Alternative high rate AD designs, such as fixed biofilm reactors, have been tested on such wastes but solids build up blocking the void spaces in the filter medium making such alternatives less promising (Bolte et al., 1986). Hybrid UASB (Lo et al., 1994) and a suspended particle-attached growth (SPAG) reactor (Cogg and Hill, 1989), are also available. The UASB is, however, the standard of high rate AD, so a small UASB like sludge bed reactor design was chosen for the present study to test the possibilities of high rate AD slurry treatment.

The objective of this study was to examine the efficiency, flexibility and stability of manure AD treatment in sludge bed reactors. The process capacity and robustness was evaluated by measuring manure degradation, development in microbial communities and product formation for a wide range of loading rates, including loads that are much higher than what is expected to be required or optimal. The study is relevant for the development of efficient wet organic waste AD with low energy density and high particulates contents in general (e.g. manure, wastewater treatment plant sludge, aquaculture waste sludge) and it may be decisive for the development of sustainable solutions to recover energy for slurry type manures.

2. Materials and Methods

2.1 Manure properties and handling

The process feed was pig manure slurry regularly collected from a production farm in Porsgrunn, Norway. The manure comes from barns that contains 105 sows, 315 “farrow to finish” and 545 weaners that are fed protein concentrate (14.6 % crude protein) added some grass/straw. Wood shavings and straw are used as bedding material. The manure is transported into a storage pit where it is diluted about 30 % by wash water from regular barn washing routines. This mixture is what we define as manure slurry. The HRT of the storage pit varies from 70 to 90 days, which has no significant effects on manure composition (Bergland et al., 2014). The manure separated by gravity into three distinct layers (Fig. 1).

The middle layer, termed the manure liquid fraction (Table 1), was siphoned from the middle layer and used without any filtering. The liquid manure was stored at 4°C until use.

Table 1. Properties of the liquid pig manure used as substrate (Average and Std. Dev.).

Property	Average ± SD
pH	7.3 ± 0.3
COD_T (g L^{-1})	28.1± 2.7
COD_S (g L^{-1})	16.0 ± 2.8
COD_{VFA} (g L^{-1})	12.2 ± 1.1
Acetate (g L^{-1})	5.5 ± 0.8
Propionate (g L^{-1})	1.9 ± 0.4
Butyrate + iso-butyrate (g L^{-1})	1.2 ± 0.2
NH_4 – N (g L^{-1})	2.35 ± 0.04
Alkalinity (g L^{-1})	8.7 ± 0.8
TS (g L^{-1})	14.5 ± 1.5
VS (g L^{-1})	7.3 ± 1.5
TSS (g L^{-1})	6.2 ± 2.7
VSS (g L^{-1})	5.1 ± 1.8

2.2 Reactor design and start up

The reactor is a simplified UASB (Fig. 2a) made of a 370 mL glass vessel with 345 mL liquid volume, height 130 mm and diameter 60 mm. The substrate inlet is a central tube ending 10 mm above the reactor bottom, with a horizontal plate at the end to improve distribution of the substrate below the sludge bed. The lab-scale process line is presented in Figure 2b. Suspended solids are separated inside the reactors to retain biomass while the gas and liquid is separated outside the reactors to ease operation in such small scale reactors. The substrate tank is kept at 4 °C.

Four identical reactors were operated for 68 days. The inoculum was based on granules (70 g L^{-1} VSS) from a UASB reactor treating pulp and paper process wastewater at “Norske Skog Saubrugs” in Halden, Norway. Half of the reactor volumes were filled with granules. Two of the reactors had been fed pig manure for 6 months as an adaption period prior to the experiment. The other two were inoculated using granules without any adaptation (these granules were stored at 11 °C for 6 months with no feed prior to the experiment). The reactors with granules not adapted to pig manure were started at a HRT of 42 hours (medium rate) while the reactors with adapted biomass were started at 8.5 hours HRT (high rate). Nearly constant HRT was maintained after start up until stable biogas production was established. Then an increase of the feed flow of 5 % was imposed every day.

The reactors were fed intermittently, 25 mL each time which is < 1/10 of reactor liquid volume implying > 10 feedings for each HRT. It is therefore reasonable to assume continuous flow in the mass balance analysis of the process. Feed flow increases were obtained by increasing the feeding frequency.

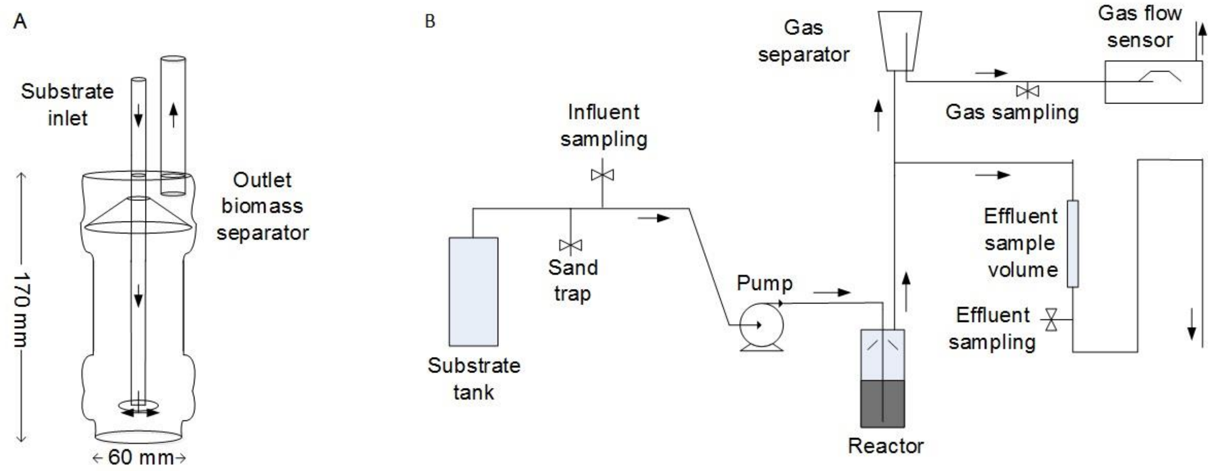

Figure 2. A) Sketch of lab-scale AD reactor with central inlet and separator. B) Diagram of lab-scale process line.

2.3 Analysis

Biogas, inflow and outflow liquid samples were collected twice a week. Total chemical oxygen demand (COD_T), soluble COD (COD_S), total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), pH, alkalinity, NH_4^+-N, VFA's (acetate, propionate, butyrate, iso-butyrate, valerate, iso-valerate, iso-caprionate and caprionate) and gas composition were analyzed.

Gas production (L d^{-1}) and reactor temperature were monitored continuously online. The biogas flow was measured using a volumetric gas meter working according to the same principle as used by Dinamarca and Bakke (2009). The reactors were kept at 35 °C in a water bath.

COD was measured according to US standard 5220D (APHA, 1995). For COD_S determination the samples were first centrifuged at 10000 rpm for 30 minutes and then filtered (0.45 µm). Alkalinity was measured by titration according to US standard 2320B (APHA, 1995).

NH_4^+-N concentration was analyzed on filtered samples (0.2 µm) by ion chromatography using an DX-500 ion chromatographic analyzer equipped with a conductivity detector, a SCS1 cation-exchange column (4x250 mm) in combination with a Dionex IonPac PCG1 (4x50mm) guard column. 4 mM methane-sulfonic acid was used as the mobile phase. The oven temperature was kept constant at 35 °C.

VFA's were measured by gas chromatography (Hewlett Packard 6890) with a flame ionization detector and a capillary column (FFAP 30 m, inner diameter 0.250 mm, film 0.5 µm). The oven was programmed to go from 100 °C, hold for one minute, to 200 °C at a rate of 15 °C min^{-1}, and then to 230 °C at a rate of 100 °C min^{-1}. The carrier gas used was helium at 23 mL min^{-1}. The injector and detector temperatures were set to 200 °C and 250 °C, respectively.

Gas composition (CO_2 and CH_4) was quantified by gas chromatography (Hewlett Packard 5890A) equipped with a thermal conductivity detector and two columns connected in parallel: Column 1, CP-Molsieve 5A (10 m x 0.32 mm) and Column 2, CP-PoraBOND Q (50 m x 0.53 mm). The gas carrier was argon at 3.5 bar pressure. The oven temperature was kept constant at 40 °C.

2.4 DNA extraction, PCR, DGGE and statistical analysis

Samples for microbial analysis were taken from the sludge trap of the reactors at days 35, 61 and 68 of the experiment. Total DNA was extracted from the sludge samples by using the PowerFecal DNA Isolation Kit (MoBio) as described by the manufacturers. For bacteria, the v3 region of the 16S rRNA gene was amplified with the primers GC-338F (5'-cgcccgccgcgcgcggcgggcggggcgggggcacgggggg actcctacgggaggcagcag-3') and 518R (5'-

attaccgcggctgctgg-3') (Muyzer et al., 1993). For methanogenic archaea, PCR primers targeting the 16S rRNA gene were designed. First, conserved regions of the 16S rRNA gene were identified by using alignments of methanogenic archaeal sequences downloaded from the Ribosomal database project (RDP). The Probematch tool of RDP was used for optimization of primer sequences and improving coverage. The resulting primers, GC-624F (5'-cgcccgccgcgcgcggcgggcggggcgggggcacgggggg caccdrtggcgaaggc-3') and 820R (5'-gccrattcctttaagtttca-3'), was employed to amplify the v5 region of the 16S rRNA gene. PCR reactions were performed using the Taq PCR Core Unit Kit (Qiagen) and 0.3 µM of each primer, and run for 35 cycles of 95 °C for 30 seconds (s), 53 °C for 30 s, and 72 °C for 60/90 s for bacterial/archaeal PCR products, respectively. The PCR products were analyzed by denaturing gradient gel electrophoresis (DGGE) (Muyzer et al., 1993) with the INGENYphorU DGGE system (Ingeny) and 8 % acrylamide gels with a denaturing gradient of 35–55 % for bacterial PCR products and 35-50 % gradient for methanogenic archaeal PCR products, as described in (Bakke et al., 2013).

The Gel2K program (Svein Nordland, Department of Microbiology, University of Bergen, Norway) was used for converting band profiles in DGGE images to histograms, where the peaks correspond to DGGE bands. Peak area matrices, reflecting the band intensities, were exported to Excel spread sheets and used for statistical analysis. Individual peak areas were normalized by dividing on the sum of the peak areas for the relevant DGGE profile. Statistical analyses were performed using the program package PAST version 2.17 (Hammer et al., 2001). Bray-Curtis similarities (Bray and Curtis, 1957) were used to compare DGGE profiles, and was calculated based on square root transformed peak areas to reduce the impact of strong bands. Ordination based on Bray-Curtis similarities were performed using non-metric multidimensional scaling (NMDS; Taguchi and Oono, 2005). PERMANOVA was used for testing differences in average Bray-Curtis dissimilarities between groups of samples (Anderson, 2001).

3. Results and Discussions

All four reactors produced biogas from day one and stabilized after 35 days of constant hydraulic load. Followed by 33 days with 5 % daily feed flow increase giving the reactors HRT from 42 to 8.5 h and from 8.5 to 1.7 h HRT for “medium rate” and “high rate”, respectively. Biogas production increased with load during the whole experiment with low standard deviations between the parallel reactors.

3.1 Stability

In all the reactors the biogas production was still increasing, due to the increasing load, when the experiment was stopped. No foaming, typically experienced in manure AD (Hill and Bolte, 2000), or significant pH changes were observed. The average effluent pH in all 4 reactors was 8.0 ± 0.1 having a slightly lower influent average pH of 7.3 ± 0.3. The alkalinity was also stable with similar effluent alkalinities of 10.6 ± 0.8 g L^{-1} (high rate case) and 11.0 ± 0.9 (medium rate case). No visual signs of process failure or instability were observed even at the highest OLR of 400 g COD L^{-1} reactor d^{-1} tested, implying that liquid pig manure sludge blanket AD can be a very robust process (chemical signs of process instability are discussed below). The reactors also showed remarkable stability and adaptation to the daily loading rate changes. Stable performance has also been reported for attached growth reactors fed liquid pig manure (Bolte et al., 1986) at loads in the lower range tested here. The observed robustness and process stability is especially important for farm and other small scale AD applications without dedicated process operators.

3.2 Capacity

The methane production rate and yield, VFA and COD results are evaluated to establish process efficiency and capacity of the process. The daily average methane production rate during the daily 5 % load increases are given in Figure 3a. The maximum rate was 37 L CH_4 L^{-1} reactor d^{-1} (= 93 g COD L^{-1} reactor d^{-1}) at HRT = 1.7 hours. This is about fifty times higher production rate than reported for conventional stirred tank AD processes operated on manure alone. The methane yields were 0.47 at HRT 42 – 17 hours and decreased to 0.24

g COD methane g^{-1} COD_T manure at HRT 1.7 hours. The yield on liter basis was 5.4 L methane per liter liquid manure, decreasing to 2.6 L methane per liter liquid manure (Fig. 3b) for the lowest HRT. The loading, biogas production, substrate COD removal and effluent concentrations are given in Table 2.

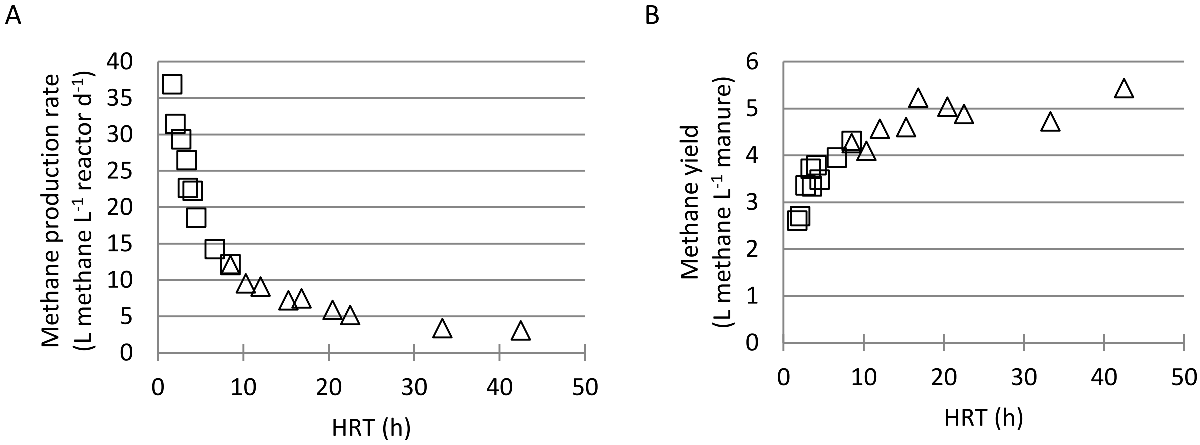

Figure 3. Average methane production rate (A) and yield (B) in both medium (∆) and high (□) rate reactors.

The COD removal, measured as COD_T, COD_S and $COD_{VFA,}$ (influent values in Table 1) varied between 24-68 %, 38-65 % and 46-90 %, respectively (Table 2). The observed 55 % COD_T reduction at HRT 17 hours corresponds well with results from similar cases reported by Kalyuzhnyi et al. (1999) and Kang et al. (2003). No published results are found to compare the highest rates investigated here. The effluent COD concentrations achieved here are probably not as low as achievable in a steady feed operation. The daily 5 % load increases used here to test the robustness of the reactors are not conducive to maximize transformation efficiency.

3.3 VFA

Process efficiency can be further elucidated from the measured VFA concentrations (COD_{VFAs}) during the experiment (Table 2). VFA was removed by 86 % - 90 % in the reactors at the start of the load increase. The effluent acetate concentration (Table 2) remained quite low during the experiment, implying robust methanogenesis except at the highest loads. The yield of removed acetate from the influent COD_T remained constant during the experiment

(Fig. 4). Propionate removal reduced with the load increase, but this did not cause other instability symptoms than lowered methane yield (g COD CH_4 g^{-1} COD_T feed) even though virtually no propionate was removed at the highest loads. Biogas methane content (%) and pH were constant even at decreasing ratio of acetate/propionate (Table 2), confirming process stability.

The reduced propionate removal can be explained by low growth rate and inhibition due to high levels of acetate and/or hydrogen since high concentrations of these propionate removal products are thermodynamic unfavorable (Batstone et al. 2002) and can occur during load increase. During constant feed operation propionate accumulation may be avoided. The increasing feed flow rate used to induce the load increase could also have caused a washout of some dispersed biomass especially at the higher flows, worsening the situation for the propionate removal organisms.

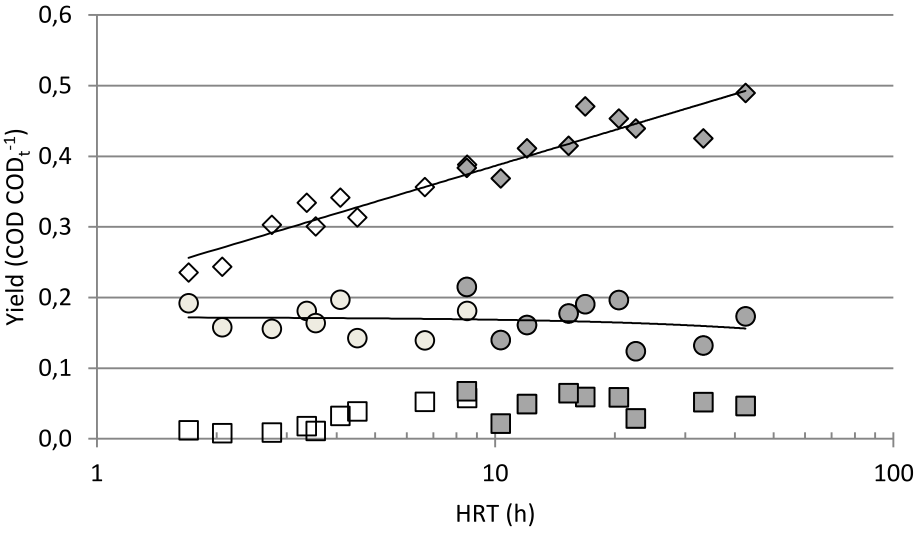

Figure 4. Produced biogas (◊), removed acetate (○) and removed propionate (□) as yield of influent COD_T. Medium rate symbols are filled and high rate symbols are unfilled.

Propionate has been recommended as state indicator, together with acetate and biogas production, to monitor manure digesters due to the slow growth of propionate degraders (Boe et al., 2010). The observations discussed above confirm that propionate degradation can be an AD rate limiting step and propionate therefore is a useful state indicator.

3.4 Microbial communities

The microbial communities in the reactors were compared at three different time points. Non-metric multidimensional scaling of Bray-Curtis similarities indicated that both the bacterial and the archaeal communities of the reactors differed with respect to the type of granule inoculum used (Fig. 5).

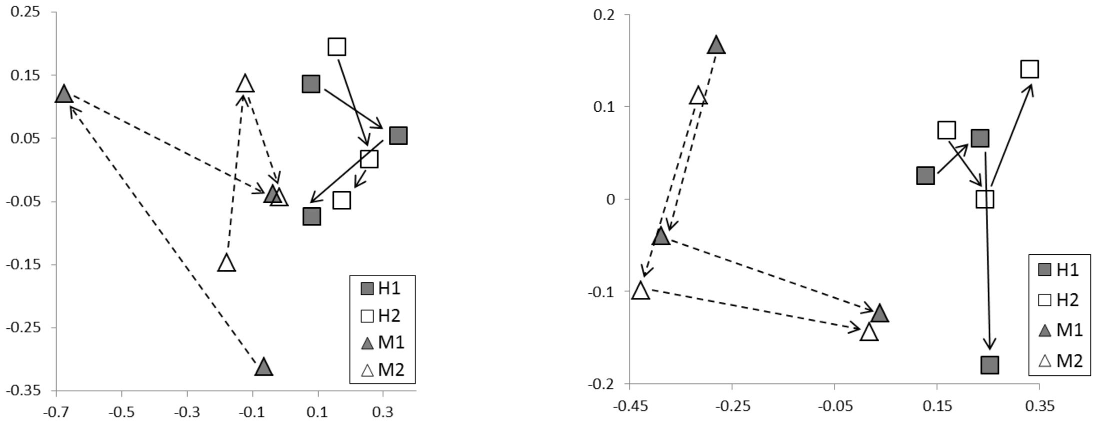

Figure 5. NMDS ordination based on Bray-Curtis similarities for comparisons of bacterial (A) and archaeal (B) communities in the high (H) and medium (M) rate reactors at day 35, 61, and 68 of the experiment. The arrows indicate the time course of the samples.

A PERMANOVA test confirmed that there were significant differences in microbial communities between the reactors inoculated with pre-adapted granules and the reactors inoculated with non-adapted granules, both for bacteria ($p = 0.003$) and archaea ($p = 0.002$). Furthermore, average Bray-Curtis similarities show that the microbial communities in the high rate reactors and the medium rate reactors became more similar with time. The average Bray-Curtis values increased from 0.63 ± 0.03 to 0.77 ± 0.06 from day 35 to day 68 for bacteria and from 0.64 ± 0.04 to 0.75 ± 0.05 for archaea. This may imply that the differences in loading rate imposed on the reactors have less effect on the reactor microbiota than the feed composition.

3.5 Process implications

The results show that gravity settled pig manure is a suitable substrate for sludge bed AD in spite of having particulates content above the recommended range for UASB feeds (Tchobanoglous et al., 2003). The manure fraction tested here has similar composition to other slurries, such as wastewater sludge, fish pond aquaculture sludge and other types of manure, encompassing nearly half of all wastes deemed suitable for AD, implying that a large portion of wet organic wastes can be treated by high rate AD.

The biogas yield was 0.47 g COD methane g^{-1} COD_T manure from HRT 42 to 17 hours, decreasing to 0.24 at HRT 1.7 h (Fig. 4). This implies that HRT > 17 h is adequate to obtain high energy recovery yield and production rates up to 20 g COD methane L^{-1} reactor d^{-1}.

There is a large trade-off between production rate and yield at the highest loads imposed. This can partly be explained by propionate degradation lagging behind in the AD chain reactions. It is likely that this limitation would lessen if steady state was allowed to establish, but some yield loss at high production must be expected. It is still likely that high production during periods of high demand can have greater value than the loss in total production caused by temporary low yield, at least down to HRT = 4 h (Fig. 3 and 4).

Very high and changing loads imposed here did not cause process failure. This suggests that such processes can be operated safely without much monitoring in the whole range tested, up to 400 g COD L^{-1} reactor d^{-1}. The result also demonstrates that it is possible to turn biogas production up and down depending on energy demands, but this must be done with caution. The reduced propionate removal caused by a 5 % load increase (Fig. 4) can be seen as a stress symptom, suggesting that faster changes can be risky but achievable.

The microbial communities in the reactors inoculated with pre-adapted granules and non-adapted granules were significantly different with respect to both bacteria and archaea, but became more similar with time. The relatively fast adaptation to manure implies that non-adapted sludge can be used to start sludge bed bioreactors for treatment of pig manure.

Cheap and mechanically simple processes are also required to make manure AD economically sound. The extreme high rate AD obtained here demonstrates that it is possible to treat manure in small and thereby presumably cheap digesters. Mechanical simplicity was achieved by not using recycle flow to fluidize the active biomass (as opposed to standard UASB design). The inflow, controlled with a timer (on/off), hit the reactor bottom in pulses as an alternative way to fluidize the sludge (Fig. 2). The strongest mixing occurred during feeding while it was observed that gas production maintained mixing between feedings. Full scale tests of an AD sludge bed reactor design without recycle will be tested next.

A rather compact sludge bed was observed at the lowest loads while a more expanded bed was observed as the loading increased. The biomass was fluidized to almost fill the whole reactor volume at the highest load, with the potential for biomass washout. This did not occur to any great extent but VFA data suggest a slight loss of biomass with increasing flow, especially at the highest flows, as discussed above.

Expanded beds not fully fluidized could trap organic particulates (Tchobanoglous et al., 2003). This was the case here judging from the removal rate of COD_T (Fig. 6) which is slightly larger than the methane production rate. Particles evidently contributed to the methane production since the COD_S removal rate was less than the methane production rate. This effect appears, however, to be valid for fully fluidized sludge beds also, since the relationships between COD_T, methane and COD_S transformation were the same in the whole range tested.

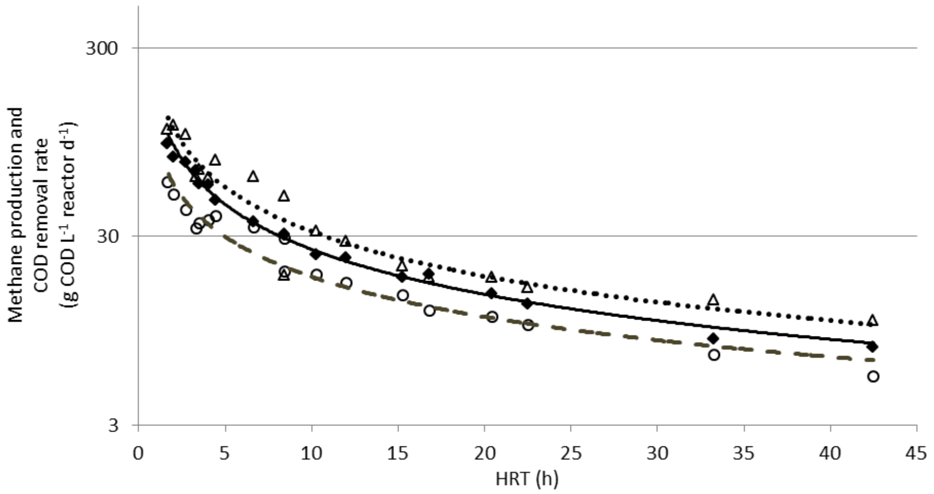

Figure 6. Methane production rate (▬ ♦) compared to the removal rate of COD$_T$ (···· ∆) and COD$_S$ (- - - ○).

Table 2. Reactor conditions, biogas production and effluent concentrations during 33 d of daily 5% feed flow increase.

			OLR			Biogas			Removal of effluent			Effluent concentrations							
Time (d)	Rate	HRT (h)	OLR (g COD_T L^{-1} d^{-1})	OLR (g COD_S L^{-1} d^{-1})	OLR (g COD_{VFA} L^{-1} d^{-1})	Biogas rate (g COD CH_4 L^{-1} d^{-1})	Biogas yield (g COD g^{-1} COD_T feed)	CH4 %	% COD_T removed	% COD_S removed	% COD_{VFA} removed	COD_T (g L^{-1})	COD_S (g L^{-1})	Acetic acid (mg L^{-1})	Propionic acid (mg L^{-1})	Hac / HPr molar ratio	pH	Alkalinity (g L^{-1})	NH_4-N (g L^{-1})
35	medium	42	16	10	6	8	0.51	80.7	68	64	86	9	7	670	651	1.3	8.0	11.3	2.3
40		33	20	13	7	9	0.44	80.3	69	66	89	9	6	631	332	2.3	8.0	11.1	
47		23	30	19	13	14	0.46	80.0	54	59	86	13	6	881	480	2.3	8.1	11.5	
50		20	33	21	15	16	0.47	80.5	55	59	82	15	6	868	778	1.4	7.9	11.6	
54		17	40	25	17	20	0.49		45	53	81	15	8	657	887	0.9	8.3		2.37
57		15	44	28	19	19	0.43		47	58	81	15	7	614	850	0.9	7.9	9.5	
61		12	56	35	24	24	0.43	79.7	50	53	76	14	8	720	1106	0.8	8.0		
64		10	65	41	34	25	0.38	79.3	49	50	67	14	8	1306	1679	1.0	7.9	8.9	
68		8.5	79	50	37	32	0.40	78.9	24	43	76	21	9	1036	1074	1.2	8.1		2.35
35	high	8.5	79	50	30	32	0.40	81.3	62	65	90	11	6	446	321	1.7	8.0	11.6	2.3
40		6.7	101	63	33	38	0.37	81.4	61	64	90	11	6	390	293	1.6	8.0	10.8	
47		4.5	150	94	65	49	0.33	81.1	51	54	74	14	7	846	1265	0.8	8.1	10.6	
50		4.1	165	103	75	59	0.36	81.2	37	47	67	18	8	915	1650	0.7	7.9	10.6	
54		3.4	201	126	87	70	0.35		31	33	60	19	11	971	1845	0.6	8.1		2.32
57		3.5	191	119	80	60	0.31		36	40	59	18	10	864	1858	0.6	7.8	9.4	
61		2.7	245	154	105	77	0.32	79.3	42	38	59	16	10	828	1937	0.5	8.0		
64		2.1	327	205	171	83	0.25	77.0	36	33	56	18	11	1636	2103	1.0	7.9	9.3	
68		1.7	397	249	187	97	0.24	76.4	28	38	46	20	10	2051	1881	2.3	8.1		2.3

4. Conclusion

The sludge bed AD reactors performed well when fed pig manure slurry, gradually increased from moderate to very high feeding flow rates (HRT from 42 to 1.7 h). This implies that gravity settled pig manure is a suitable substrate for high rate sludge bed AD.

The maximum biogas production rate of 97 g COD L^{-1} reactor d^{-1} was obtained at the highest load tested (OLR = 400 g COD L^{-1} reactor d^{-1}). No foaming, pH reduction or process failure was observed during the experiments, but VFA accumulation was observed at the highest OLRs.

The yield was ~0.47 g COD methane g^{-1} COD_T manure from HRT 42 to 17 h, decreasing to 0.24 at HRT 1.7 h. This implies that the HRT > 17 h gives high energy yields at production rates up to 209 g COD methane L^{-1} reactor d^{-1}. Reduced yields at higher production may be an acceptable temporary loss during periods of high energy demands.

Some entrapment and degradation of particulates occurred at all loads but was reduced with falling HRT.

Transitions from low to high loads can stress AD but this process handled 5 % daily load increases well with propionate accumulation as the only stress symptom down to HRT= 4 h. The increase in reactor propionate levels with increasing loads shows that propionate degradation can be the rate limiting step, explained by growth rate kinetics inhibition and dispersed biomass loss with increased liquid flow.

A relatively fast adaptation to manure of the microbial communities implies that non-adapted sludge can be used as inoculum to start sludge bed bioreactors for treatment of pig manure.

Sludge bed AD, without water recycle to fluidize the biomass, evidently function well with pulse feeding as alternative approach to obtain the required mass transfer. The degree of sludge bed expansion was observed to increase with load.

High rates in mechanically simple reactors imply a large potential for reduced costs, improving the possibilities of profitable methane production. The high process capacity, stability and robustness to changing loads observed imply that efficient AD of wet organic wastes with high particulates contents is achievable.

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