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ORIGINAL PAPER

Digestion of sand-laden manure slurry in an upflow anaerobic solids removal (UASR) digester

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Abstract Studies on the performance of a laboratory scale upflow anaerobic solids removal (UASR) digester were carried out using sand-laden cow manure slurries having total solids (TS) concentration as 50 and 100 g/l. Hydraulic retention time (HRT) was maintained as 32.4 days, which resulted in the volatile solids (VS) loading rates of 1 and 1.64 g/l d. The UASR system was designed to remove sand from the manure slurry, while anaerobically digesting biodegradable solids inside a single reactor. To enhance the contact of microorganisms and substrate, the liquor from the top of the digester was recirculated through the bed of settled solids at its bottom. Volatile solids reduction through this process was observed to be 62% and 68% in the case of feed slurries having TS concentration as 50 and 100 g/l (referred in the text as 5% and 10% feed slurries), respectively. The methane production rates were observed to be 0.22 and 0.38 l/l d, while methane yield was 0.21 and 0.27 l CH_4/g VS loaded, for 5% and 10% feed slurries, respectively. This indicates that the increase in the VS loading had a positive impact on methane production rate and methane yield. It would be of interest to study the performance of a UASR digester at higher solids loadings and with longer solids retention times. Nonetheless, the presented study showed that sand-laden manure slurries can be successfully digested in a UASR digester producing methane energy equivalent to 4 kW h per m^3 of digester volume per day.

Keywords Anaerobic · Digestion · Manure slurry · Methane · Mixing · UASR

Introduction

Animal manure is a valuable biomass resource, which can be anaerobically digested to produce methane gas—a sustainable source of energy. The United States alone produces approximately 230 million tons of dry manure every year (Sheffield 2002). The mishandling of manure often leads to numerous environmental problems, such as surface and ground water contamination and greenhouse gas (methane) emissions. Anaerobic digestion is the most commonly applied manure management option, which produces nutrient rich fertilizer and methane gas.

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Significant amounts of inert solids (sand) is often found in the manure collected from concrete floors, or from beddings. Sand is used as a favorable bedding material to avoid mastitis (Bernard et al. 2003). It is also suggested that sand based stalls are very comfortable for cows as they help to keep the cow clean and healthy, as well as promote high milk productivity (Holmes 1998). Eventually, the inert materials from beddings and floors find its way to a digestion unit along with manure. Karim et al. (2005) observed significant amount of sand and inert materials accumulation inside the digesters, while studying the effect of different modes of mixing (biogas recirculation, impeller mixed, and slurry recirculation) on the digestion process. Thus, settling of inert bedding materials inside a manure-digestion unit is a serious issue, which needs to be considered in the design of a digester.

Zeeman et al. (1997) developed an upflow anaerobic solids removal (UASR) reactor for the pretreatment of raw sewage, waste activated sludge, and dairy wastewater. The UASR approach uses a single reactor for both digestion and settled inert solids (sand) removal, which would otherwise accumulate and reduce active reactor volume and thus reducing methanogenic activity. Unfortunately, not much work has been reported on the effectiveness of UASR systems with other waste streams containing high solids concentration, such as sand-laden manure slurry.

Therefore, the present study was designed to evaluate the performance of a UASR digester as a new approach for sand-laden cow manure slurry digestion and methane production. The effect of the increased solids concentration (in the slurry) on the digester performance was studied and reported in this paper.

Materials and methods

Experimental set-up

As illustrated in Fig. 1, a laboratory scale UASR digester having a working volume of 7.46 l was fabricated out of a 6 inch diameter PVC pipe. The bottom of the reactor was made as a 60° angle hopper to collect settled solids. A

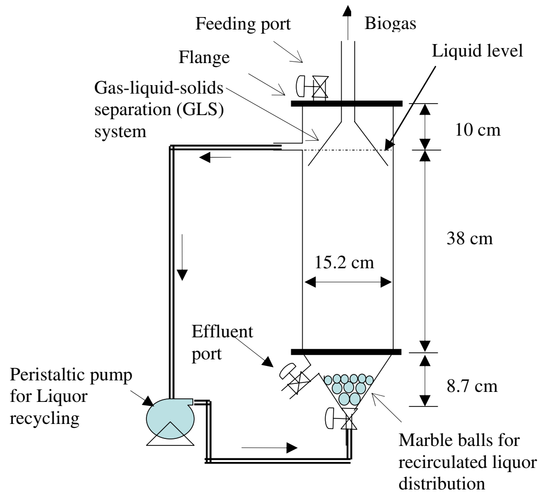

Fig. 1 Schematic diagram of the experimental set-up

gas–liquid–solids (GLS) separator system at the top of the reactor collected gas as well as minimize suspended solids from entering the recirculation line. The digester was mixed by recirculating liquor from the top of the digester through the hopper bottom. The hopper bottom was filled with marble balls (1 cm in diameter) to facilitate uniform liquor distribution. The liquor was recirculated up using a Masterflex pump from Cole Parmer Instrument Co., Chicago, Illinois, USA. The liquor recirculation flow rate (0.82 l/min) was calculated based on maintaining a constant power supply per unit volume of 8 W/m^3, assuming 100% pumping efficiency and using Eq. 1.

$$P = \rho g H Q \tag{1}$$

where P = power, Q = discharge (m^3/s), H = head of the slurry (m), ρ = density of the slurry pumped (kg/m^3), and g = 9.81 m/s^2.

Experimental conditions

The above mentioned UASR digester was inoculated with 746 ml (10% of the total working volume) anaerobic seed sludge collected from a dairy farm operated by the University of Tennessee. The seed sludge had 66.13 g/l total suspended solids (TSS) and 35.63 g/l volatile suspended solids (VSS). The remaining 90% of the working volume was filled with freshly prepared feed (manure slurry) having a dry solids concentration of 50 g/l (referred in the text as 5% feed slurry). The feed preparation procedure has been explained in the following subsection. The digester was operated at a controlled temperature of 35 ± 2°C. On alternate days, 460 ml of effluent was taken out from the bottom of the digester and replaced with the same amount of freshly prepared manure slurry to maintain a hydraulic retention time (HRT) of 32.4 days, resulting in a total solids (TS) loading rate of 1.54 g/l d (corresponding to a VS loading of 1 g/l d). The digester was operated under steady-state conditions for about 3–4 weeks. Steady-state conditions were considered to be achieved when the effluent chemical oxygen demand (COD) concentration and biogas production were within 15% of their average values (Haghighi-Podeh et al. 1995). After operating the digester for the required amount of time with 5% feed slurry, the second experimental run with 10% feed slurry (i.e., 100 g/l total solids concentration) was initiated. The change in the TS concentration in the feed slurry resulted in the TS and VS loading rates of 3.08 and 1.64 g/l d, respectively. All other operating conditions were kept the same as in the case of 5% feed slurry study, and the steady-state performance data was acquired.

Feed slurry preparation procedure

Raw cow manure was collected fresh (less than 2 days old) from the Institute of Agriculture, University of Tennessee, Knoxville, and stored in a freezer. The collected raw manure was observed to have TS and VS concentrations as 435 ± 58 and 129 ± 9 g/l, respectively. The size of the suspended solids in the collected manure varied from big chunks of wood and concrete, long straw pieces to small sand particles. Therefore, the collected raw manure was blended, screened, settled and diluted to prepare feed slurry for the above mentioned anaerobic digestion study. The blending of the manure was done at 10,500 rpm for 2 min using a household blender. Blending of the manure was for the purpose of breaking big chunks of hay, straw, and wood, which would otherwise clog the valves fitted to the digester. Tap water was then added to the blended slurry to dilute it before screening through a 2 mm sieve, followed by settling for 60 min to remove sand. Prepared slurry was diluted with tap water to achieve the required solids concentration. It is important to note that the 5% and 10% feed slurries were prepared separately, and the amount of tap water added to the blended slurry before screening was different in the two cases. Since the screened slurry in the case of 10% feed preparation was thicker than that of 5% feed, lesser amount of sand was removed through settling in the former case than the later. This resulted in significantly higher amount of inert materials in the case of 10% feed slurry than that of 5% feed slurry. The characteristics of a typical batch of both 5% and 10% prepared feed slurry are given in Table 1.

Analytical methods

Feed and effluent samples were analyzed for TS, volatile solids (VS), TSS, VSS, volatile fatty acids (VFA), total chemical oxygen demand (TCOD), and soluble chemical oxygen demand (SCOD), as per standard procedures (APHA 1998). Biogas generated in the digester was collected in a Tedlar© bag, and the biogas volume was measured using a wet gas test meter (Schlumberger Industries, the Netherlands). The composition of the biogas and the concentration of volatile fatty acids in the effluent were analyzed as mentioned elsewhere (Karim et al. 2005).

Table 1 Characteristics of the prepared feed slurry from a typical batch

Feed type	TS (g/l)	% VS	TSS (g/l)	VSS (g/l)	TCOD (g/l)	SCOD (g/l)
5% slurry	52.2	69.58	38.7	25.12	64.0	19.2
10% slurry	107.7	40.93	62.2	52.46	70.5	36

TS = total solids, VS = volatile solids, TSS = total suspended solids, VSS = volatile suspended solids, TCOD = total chemical oxygen demand, SCOD = soluble chemical oxygen demand

Results and discussion

The performance of a laboratory scale UASR digester was evaluated using sand-laden cow manure slurry. The observed performance data is presented in Figs. 2–5. Figure 2 shows that the digester took almost 5 weeks from start-up to stabilize biogas production in the cases of both 5% and 10% feed slurries, having TS concentration as 50 and 100 g/l, respectively. The average biogas production under steady-state conditions (for the last 30 days) was observed as 2.49 ± 0.31 1/d in the case of 5% feed slurry and 4.16 ± 0.37 l/d in the case of 10% feed slurry. The average biogas production rate and methane content for the two feed slurries under steady-state conditions are given in Table 2. Each value was calculated as a mean value over the last 30 day period. The biogas production rate was calculated as the volume of biogas produced per liter of digester volume per day.

The volume of biogas produced per unit weight of VS removed was calculated as 0.45 and 0.61 l for the 5% and the 10% feed slurries, respectively. The volume of biogas produced per unit weight of VS removed in the case of 5% feed slurry is significantly less than the reported value of 0.7 l/g VS removed (Persson et al. 1979). Methane yield, calculated based on the weight of the VS added every day, was observed as 0.21 and 0.23 l/g VS added for 5% and 10% feed slurries, respectively. The methane yield for 10% feed slurry is very close to that observed for

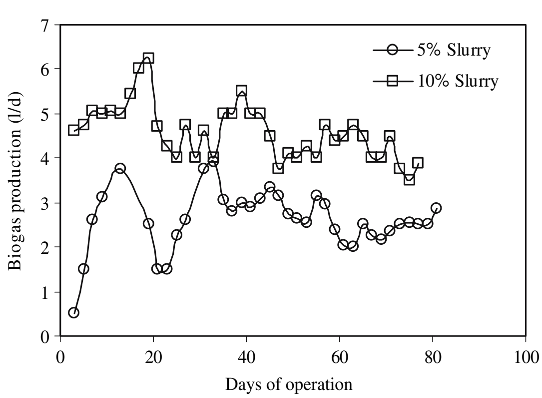

Fig. 2 Daily biogas production in the case of 5% and 10% feed slurry

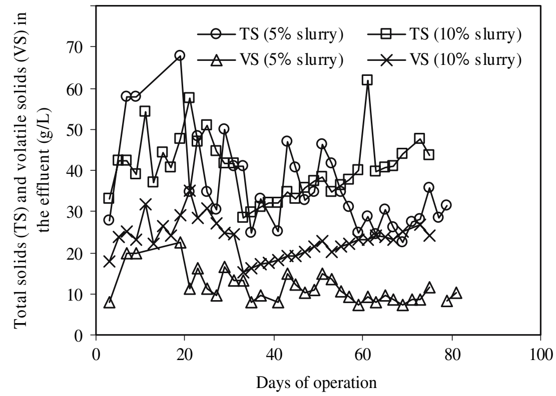

Fig. 3 Total solids (TS) and volatile solids (VS) concentrations in the effluent collected in the case of 5% and 10% feed slurry

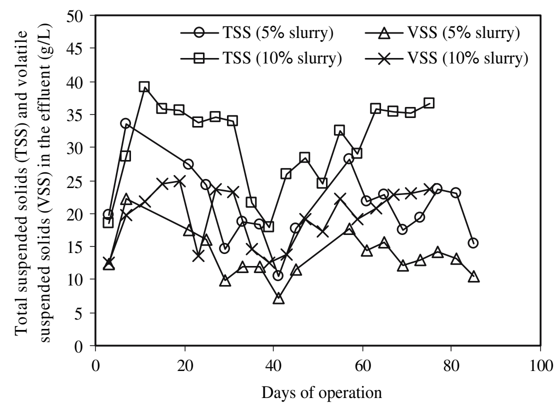

Fig. 4 Total suspended solids (TSS) and volatile suspended solids (VSS) concentrations in the effluent collected in the case of 5% and 10% feed slurry

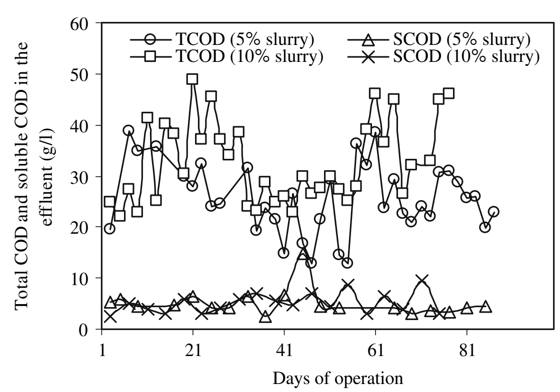

Fig. 5 Total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD) concentrations in the effluent collected in the case of 5% and 10% feed slurry

Table 2 Biogas production rate and methane content for the digesters under steady-state conditions

Feed	Biogas production rate (l/l d)	Methane content (%CH_4)
5% Slurry	0.33 ± 0.04	66.7 ± 2.84
10% Slurry	0.56 ± 0.05	68.36 ± 2.71

unmixed (0.26 l CH4 per g VS loaded), biogas recirculation mixed (0.26 l CH_4 per g VS loaded), impeller mixed (0.27 l CH_4 per g VS loaded), and slurry recirculation mixed (0.28 l CH_4 per g VS loaded) conventional digesters, operated at 2 g VS/l d loading (Karim et al. 2005). The observed methane yield is also in accordance with the reported methane yield of 0.376 l/g VS added, at a loading of 2.86 g VS/l d (Linke 1997).

The average steady-state data (for the last 30 days) of TS, VS, TSS, VSS, TCOD, and SCOD in the effluents for both 5% and 10% feed slurry studies are given in Table 3. The TS and VS reductions in the case of 5% feed slurry was observed to be 38% and 62%, respectively. In terms of mass, about 20 g of TS were removed per liter of the slurry, which is almost equal to the amount of VS removed as given in Table 3. This shows that almost all of the inert solids present in the influent came out with the effluent, and hence there was no significant inert solids accumulation inside the digester in the case of 5% feed slurry.

The data presented in Table 3 shows that the TS and VS reductions in the case of 10% feed slurry were about 60% and 68%, respectively. In another words, about 61 g of TS and 36 g of VS were removed per liter of the slurry. This indicates that along with VS some inert solids (about 24 g/l) were also removed in this process. Inert solids cannot be degraded, and hence the removal of inert solids inside the digester can only be through settling and entrapment. To account for the amount of solids that accumulated inside the digester during the 10% feed slurry study, the digester was opened at the end of the study and the solids were taken out and dried. About 428 g (dry weight) solids were found to have accumulated inside the digester, which consisted of 18 g (dry weight) of VS. Therefore, the majority of the solids accumulated inside the digester were inert material. Visually it was observed that most of the inert deposits were sand, which is also supported by the fact that the collected raw manure had significant amount of sand in it. Assuming the bulk density of sand as 1640 kg/m^3, the digester volume occupied by the deposited sand (410 g) was calculated to be about 7% of the digester active volume (7.46 l). This emphasizes the need for inert solids removal prior to the slurry being fed to the digester. Alternatively, there should be a properly designed effluent port for settled solids removal at the bottom of digester fed with slurry having a high concentration of inert bedding materials, such as sands.

Average TCOD for the 5% and 10% feed slurries were about 59 g/l and 64 g/l, which consisted of 32% and 37% soluble fractions, respectively (Table 3). It can also be noted that the difference in the total COD for the two feed slurries is not proportional to the difference they have in terms of VS. This is probably due to the fact that the slurries had high suspended solids concentration, which made it very difficult to collect representative samples for TCOD analysis. The steady-state reductions of SCOD in the case of 5% and 10% feed slurries were observed to be 79% and 75%, respectively. Volatile fatty acids concentrations in the effluents with the two feed slurries were always observed below detectable levels and pH between 7 and 7.8.

Table 3 Average steady-state value (over last 30 days) of the observed parameters for feed and effluents

	Total solids (g/l)	Volatile solids (g/l)	Total suspended solids (g/l)	Volatile suspended solids (g/l)	Total chemical oxygen demand (g/l)	Soluble chemical oxygen demand (g/l)
5% Feed slurry	51 ± 1	34 ± 2	37 ± 5	25 ± 3	59 ± 7	19 ± 1
5% Effluent	31 ± 6	13 ± 1	21 ± 4	14 ± 2	27 ± 5	4 ± 0.6
10% Feed slurry	101 ± 3	53 ± 6	51 ± 11	42 ± 10	64 ± 10	24 ± 9
10% Effluent	40 ± 4	17 ± 2	32 ± 4	21 ± 2	34 ± 8	6 ± 2

The results obtained from this study show that sand-laden manure slurry can be successfully digested in an UASR digester. As mentioned in Table 2, methane gas production rates were observed as 0.22 and 0.38 l/l d in the case of 1 and 1.64 g/l d VS loadings, respectively. The methane production rates observed during this study show that the increase in VS loading had a positive impact on the methane yield. Therefore, another set of studies is recommended to conclude an optimum loading rate for manure slurry digestion in a UASR digester. Assuming the energy content of methane gas as 10.5 kW h/m^3, methane production rate of 0.38 l/l d would result in an output energy of 4 kW h per m^3 of digester volume per day.

Conclusions

The reported study demonstrates a new approach to sand-laden manure slurry digestion in an UASR digester. Since the studied system works both as a settling unit as well as a high rate digester, the approach was found especially promising. The observed VS reductions were 62% and 68% for 5% and 10% manure slurries, respectively. Methane gas production rates were observed as 0.22 and 0.38 l/l d in the case of 5% and 10% feed slurries, which can result in an output energy up to 4 kW h per m^3 of digester volume per day. The methane yield data, 0.21 and 0.27 l CH_4/g VS added, for the two studied VS loadings of 1 and 1.64 g/l d show that the increase in the VS loading had a positive impact on the methane yield. However, it would be interesting to study its performance at higher solids loadings and with at longer solids retention times.

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