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Research Article

Effect of mixing on biogas production during mesophilic anaerobic digestion of screened dairy manure in a pilot plant

The effect of mixing on biogas production of a 1.5-m^3 pilot continuous stirred tank reactor (CSTR) processing screened dairy manure was evaluated. Mixing was carried out by recirculation of reactor content with a mono pump. The experiment was conducted at a controlled temperature of $37\pm1°C$ and hydraulic retention times (HRTs) of 20 and 10 days. The effect of continuous and intermittent operation of the recirculation pump on biogas production was studied. At 10 days of HRT, the results showed a minimal influence of recirculation rate on biogas production and that continuous recirculation did not improve reactor performance. At 20 days of HRT, the recirculation rate did not affect reactor performance. Combination of low solid content in feed animal slurry and long HRTs results in minimal mixing requirements for anaerobic digestion.

Keywords: Biogas / Dairy manure / Liquid fraction / Mixing / Recirculation

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1 Introduction

The increase in production and concentration of intensive livestock operations have resulted in greater awareness and concern for the proper storage, treatment and utilization of livestock manure. This happens in Cantabria, a region in Northern Spain with a bovine population of around 280 000 livestock units (mainly milk). Humid climate and pronounced slopes imply that the liquid fraction of dairy manure is the most problematic for hydric resources due to run-off. On the other hand, lack of sufficient land for disposal results in a surplus of nitrogen in the areas where intensive farming is concentrated. Typical disposal methods for animal manure allow for the emission of ammonia, particulate matter, unpleasant odors, volatile organic compounds and various other air pollutants, which can damage the environment and pose risks to animal and human health [1–4]. Anaerobic digestion is an alternative to traditional dairy manure management, alleviating environmental concerns and converting organic residues into two categories of valuable products. One of these, the biogas, is a renewable fuel further used to produce green electricity, heat or as vehicle fuel. The other one is the digested substrate, commonly named digestate, which is commonly used as fertilizer in agriculture [5–7].

Dairy manure composition depends on cows' diet and the conditions under which animals (dairy cows, breeding cows and calves) are kept in the farm. In addition to faeces and urine, dairy wastes contain other materials such as rests of food and bedding (straw, sand, sawdust, etc.). Many of these solids are recalcitrant or hardly biodegradable [8]. The high content of fiber contained in the manure limits the development of commercial anaerobic digestion process because the fiber is both difficult to break down and can cause clogging problems within the reactor [3].

The performance of continuous stirred tank reactor (CSTR) is affected by the hydraulic retention time (HRT) of the substrate and the degree of contact between the incoming substrate and the viable bacterial population [9]. Both parameters are dependent of the hydraulic regime (mixing) in the digester. Mixing is usually accomplished through either mechanical mixers or recirculation of digester content or biogas [9]. Although many works [9–14] have reported about mixing strategy in anaerobic digesters, there is not a clear picture about the effects of mixing on anaerobic digestion of manure. In addition, stirring systems are still one of the most critical biogas plant components due to floating or sedimenting substances.

Separation of liquid and solid fractions of manure is a solution to separate the fiber from the liquid prior to anaerobic digestion. Moreover, the separated liquid fraction, with much

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Abbreviations: COD, chemical oxygen demand; **COD_{VFA}**, COD due to volatile fatty acids; **CSTR**, continuous stirred tank reactor; **HRT**, hydraulic retention time; **OLR**, organic loading rate; **TS**, total solids; **VFA**, volatile fatty acids; **VS**, volatile solids less suspended solids content would be more easily subjected to an anaerobic process with lower mixing requirements, temperature and HRT than those for unscreened dairy manure [15, 16]. The digested liquid fraction, with improved agronomic properties, would also be in more favorable conditions to be further refined into concentrated fertilizers or to receive post-treatments in order to obtain clean water, suitable for recycling. In addition, dewatering the solid fraction lowers the cost of shipping, facilitating the export of nutrients from the areas with excess of manure and the redistribution to other areas in need of nutrients [5]. Before its transport, solid fraction can be subjected to dry anaerobic digestion and/or the composting process, which would represent an additional reserve of more stable organic carbon and nitrogen for the cultivated soil [17].

The objective of this work is to evaluate the influence of the reactor content recirculation rate on biogas production during the mesophilic anaerobic digestion of screened dairy manure in a CSTR pilot digester.

2 Materials and methods

2.1 Pilot plant

The pilot plant was projected in 2008 and inaugurated in June 2009. The pilot plant consists of a first stage of liquid–solid separation (screw press and decanter centrifuge separators devices) and anaerobic digestion (a conventional CSTR and a UASB reactor). The second stage follows the recovery of nutrients and to obtain a final liquid effluent suitable for reutilization. During the realization of the present work only the screw press separator and the CSTR were employed.

Figure 1 shows the scheme of the installation and technical parameters of the components used in the pilot plant tests. As illustrated in Fig. 1, a chopper pump was used to recirculate the manure slurry avoiding stratifications into the storage tanks and to pump the slurry up to the separator. Two mono pumps were employed for feeding the reactor and recirculation of the reactor content. Other details of the main components of the pilot plant used in this work are as follows:

(i) The CSTR digester is a cylindrical fixed dome vessel made of 304 stainless steel. Mixing is accomplished by recirculation of reactor content. It is equipped with temperature and pH probes. The digester is inside covered with epoxy painting and the exterior wall is thermally insulated to prevent heat losses. Reactor has two sampling ports, one in the effluent tube and the other in the recirculation pipe.

(ii) The recirculation pump was used to mix the reactor content and to maintain the temperature of the process since recirculation pipe passed through a heat exchanger.

(iii) Heating system: Water was used as heating fluid. It was heated up to 55°C in an electric heat accumulator tank of 500 L. The heat exchanger consists of a corrugated tube within a tube.

(iv) Biogas line: Biogas left the reactor by its own pressure passing through a catch pot and a coalescing filter to protect the biogas meter from condensates and particulate matter. Biogas production was determined by a mass flow meter. A biogas sampling port was installed between the catch pot and the mass flow meter. At the end of the line, biogas was burned in a flare.

(v) The control panel, located in a protective and closed box, contains all the electric system controls required for the functioning of the pilot plant. Heating system was commanded by the temperature probe to maintain the temperature of the digester at 37 ± 1°C.

2.2 Mode of operation

Before this experiment, the CSTR had been satisfactorily operating for more than 6 months. The reactor had been filled up with screened dairy manure allowing the growth and acclimatization of methanogenic biomass and organic matter stabilization of reactor content. It was started up at a HRT of 20 days that was progressively diminished down to 10 days.

The reactor was fed in a semi-continuous mode in cycles of 30 min. Feeding cycles were equally distributed along the day (Table 1). A purge of 75 L from the bottom of the reactor was done weekly.

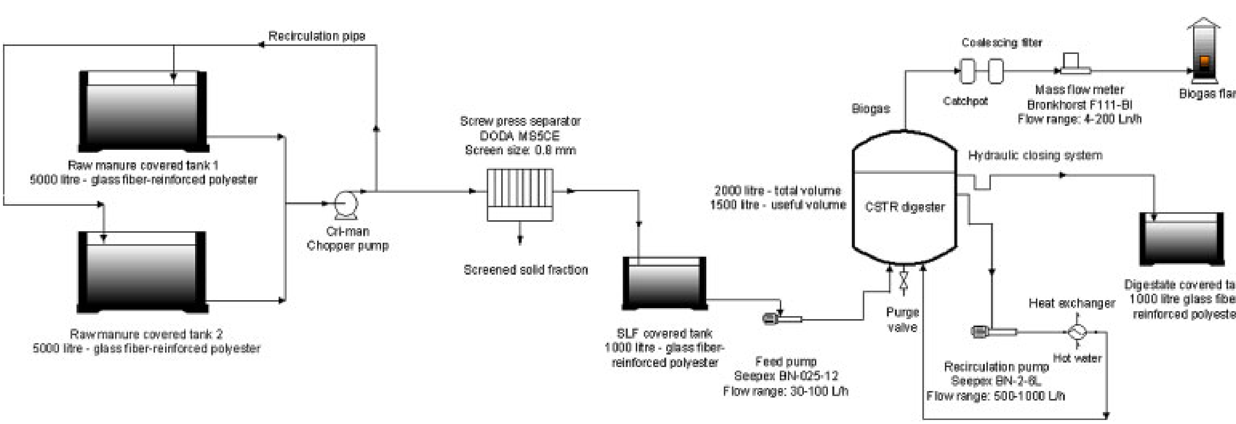

Figure 1. Scheme of the pilot installation.

Table 1. Reactor operation data

HRT (days)	Feed pump flow (L/h)	Feeding cycles a day (30 min)	Feed rate (L/d)
20	30	5	75
10	30	10	150

As mentioned previously, mixing and heating was accomplished by recirculation. Three different recirculation rates were analyzed. Under the first experimental condition (A), recirculation pump was programmed together with heat exchanging system to automatically start when temperature controller detected heating needs performing a stable reactor temperature at $37\pm1^{\circ}C$. This way, recirculation pump only functioned to maintain the temperature of the reactor. The number of hours that recirculation pump was running were registered. For the second experimental condition (B), recirculation pump was programmed to work ten times a day in cycles of 30 min. Recirculation pump was programmed to work at the same time as the feeding pump to enhance mixing. In addition, recirculation pump was also programmed together with heat exchanging system to maintain the temperature reactor. The number of hours that recirculation pump was on were registered. Under the third experimental condition (C), the recirculation pump was programmed to function 24 h per day in order to maximize the degree of mixing within the reactor. The flow rate of the recirculation pump was set at 1000 L/h. The experiment was carried out at 10 and 20 days HRT.

2.3 Feed preparation

Dairy manure was collected from the dung pit of a near 500 free stall dairy cow farm equipped with scrape systems. Manure was extracted from the dung pit by a tractor equipped with a vacuum tank system and then transported and discharged into the raw manure tanks. Dairy manure was screened in the pilot plant by a screw press separator (0.8 mm mesh). Feeding tank received the screened liquid fraction that served as feeding of the CSTR reactor. The feeding tank was filled up and when it was getting empty, it was cleaned with a vacuum cleaner to remove sediments from the bottom and filled again.

2.4 Analytical techniques

Volatile fatty acids (VFA) were determined using a HP6890 gas chromatograph (GC) fitted with a 2-m 1/8 in glass column, liquid phase 10% AT 1000, packed with the solid support Chromosorb W-AW 80/100 mesh. Nitrogen was the carrier gas, flow rate 14 mL/min, and a FID detector was installed. Total VFA concentrations are expressed in mg theoretical COD (chemical oxygen demand)/liter units. As indicated before, the volume of biogas generated in pilot plant CSTR reactor was measured by a mass flow meter and registered by an electronic unit. Biogas composition was assayed on a 2-m Poropak T column in a HP 6890 GC system with helium as carrier gas, flow rate 15 mL/min, and TCD detector. All the gas measurements are expressed at $0^{\circ}C$ and standard pressure of 1.013×10^5 Pa. All other analyses – TS (total solids), VS (volatile solids), pH, COD, Total Kjeldahl Nitrogen (TKN-N), NH_4^+N, Total Phosphorus (P_T) – were performed according to standard methods [18]. All the analyses were performed in duplicate; the values shown are the mean ones.

3 Results

3.1 Feed characteristics

The screw press used produced a solid and a liquid fraction. The screened liquid fraction was the feed of the CSTR. Characteristics of screened liquid fraction during the experimental period are presented in Table 2.

3.2 Biogas productions at different recirculation rates

The experiment started at 10 days HRT. First, during 10 days, recirculation pump was limited to work the minimal time maintaining reactor temperature (condition A). The next 10 days, recirculation pump was set at condition B and afterwards between days 20 and 30, recirculation pump functioned 24 h per day (condition C). At day 30, HRT was set at 20 days and a period of time of 10 days was necessary to reach the new steady state conditions. From days 40 to 70, conditions of mixing A, B and C were performed similarly to the previous case.

The biogas produced in the digester was recorded daily, whereas methane content of biogas was analyzed every 5 days. Figure 2 shows the volumetric biogas production rate and methane content of biogas during the different phases of the experiment.

3.2.1 Biogas production at 10 days HRT

As shown in Fig. 2, between days 0 and 30, the CSTR had the same experimental conditions except for recirculation rate. At 10 days HRT, the applied organic loading rate (OLR) was 4.5 kg VS/m^3 d. During this period, biogas production was stable with average productions of 1.26, 1.34 and 1.30 m^3/m^3 d for mixing conditions A, B and C, respectively. The highest biogas production was obtained under medium recirculation rate condition (B). When the recirculation pump functioned

Table 2. Characteristics of the screened liquid fraction

Parameter	Mean $\pm$ SD
TS (%)	6.1 ± 2.2
VS (%)	4.5 ± 1.9
pH	6.5 ± 0.2
COD_T (g/L)	57.6 ± 3.1
COD_{VFA} (g/L)	13.7 ± 1.3
TKN-N (g/L)	3.8 ± 0.2
NH_4^+-N (g/L)	2.2 ± 0.6
P_T (g/L)	1.1 ± 0.1

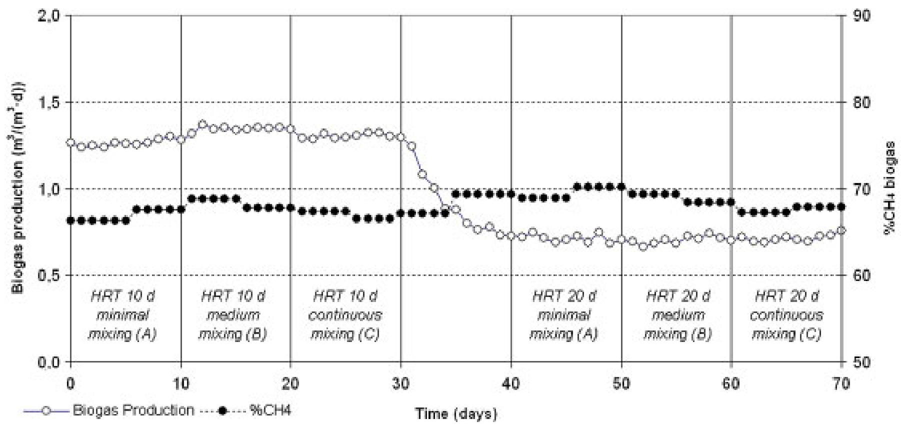

Figure 2. Volumetric biogas production rate and methane content of biogas.

continuously (C), biogas production was 3.0% less than that reached under intermediate mixing conditions (B). When recirculation rate was the minimum (A) biogas production was 6.0% less than the maximum obtained. Biogas methane content always remained close to 67%. In Table 3, the number of hours that recirculation pump was running and the characteristics of effluents for the three experimental conditions are given.

For the three experimental conditions, COD_T and VS reduction were similar, about 36 and 38%, respectively. The main difference in effluent characteristics was the higher presence of VFA (Table 3) under condition A. Anyway, the differences were minimal.

3.2.2 Biogas production at 20 days HRT

At day 30, HRT was set at 20 days. Under these conditions, the OLR applied was 2.3 Kg VS/m^3 d. As Fig. 2 shows, biogas production rapidly decreased and at day 40, biogas production reached a quite stable value around 0.70 m^3/m^3 d. For this HRT, no differences were observed among the three different mixing conditions. Mean biogas production values were 0.71, 0.70 and 0.71 m^3/(m^3 d) for conditions A, B and C, respectively (Table 4). Methane content of biogas ranged from 67.2 to 70.2%.

Removal percentages of COD_T and VS were 43 and 46%, respectively. Obviously, due to the lower OLR applied, removal percentages were higher than those obtained for 10 days HRT. There was no VFA accumulation in the effluents.

4 Discussion

The data obtained showed that at a long HRT, the degree of mixing by recirculation did not affect the operation of the reactor. For the three conditions studied at 20 days HRT, reactor operation was almost identical with similar biogas production and effluent characteristics. However, when operated at shorter HRT (10 days) and at an OLR of 4.5 Kg VS/m^3 d, some differences were observed in the production of biogas from the reactor. The best results were obtained for an intermittent recirculation running at the same time than feeding, facilitating feed mixture with the content of the reactor. When the recirculation pump was programmed for minimum operation with the only purpose to maintain the temperature of the reactor, the biogas production decreased 6.0%. Keeping the recirculation pump running 24 h a day did not mean any improvement in the production of biogas. Mixing more than required has got no sense because reactor performance does not improve and the energy used to mix reactor content would be wasted. In this sense, Karim et al. [9] found no differences in the behavior of six digesters with different mixing conditions. They attributed it to the low solids concentration in the fed animal slurry (5% TS) or the long HRT applied (16.2 days). In another work, Karim et al. [19] concluded that the role of mixing becomes more important with an increase of TS feed concentration, stating that with 10–15% TS manure slurry, mixed digesters produced more biogas than unmixed digesters. In the present work, screened dairy manure had a TS concentration of 6.1% and the performance of the digester at 20 days HRT is in accordance with that reported by Karim et al. [9, 19]. However, at 10 days HRT, the mixing strategy showed some influence on biogas production. The reason for this can be the high OLR applied. VFA presence in effluents indicates that reactor was close to its limit. Under these conditions, the higher degree of mixing resulted in higher biogas production. The reason for the better performance of the reactor under mixing conditions B at 10 days HRT seems to be the fact that feeding and recirculation pumps were running at the same time enhancing mixing of the feed with the reactor content. Continuous mixing did not improve biogas production showing that intermediate mixing appears to be most optimal for substrate conversion as reported by Smith et al. [10] and Dague et al. [20]. Moreover Kaparaju et al. [12] studied the influence of mixing with cattle slurry 6.5–7.5% TS, reporting that mixing improved process performance and methane production in CSTR reactors. On the other hand, higher methane production rates in unmixed digesters have been reported by Ghaly and Ben-Hassan [11].

Based on the results for the different mixing conditions, we can conclude that anaerobic digestion of screened liquid fraction with 6% TS concentration was minimally affected by recirculation rate at a HRT as short as 10 days. Optimization of mixing is required to maximize reactor performance, especially to enhance mixing of the feed with reactor content but continuous recirculation did not improve biogas production

Table 3. Hours of recirculation and effluent characteristics at 10 days HRT

	Condition A	Condition B	Condition C
Hours recirculation pump running a day	2.5	6.8	24
pH	7.7±0.1	7.8±0.1	7.8±0.1
COD_T (g/L)	35.9±2.7	36.6±2.4	37.5±1.5
VS (g/L)	26.3±1.1	27.2±1.3	28.9±0.8
COD_{VFA} (mg/L)	954±120	650±96	735±156

Table 4. Hours of recirculation and effluent characteristics at 20 days HRT

	Condition A	Condition B	Condition C
Hours recirculation pump running a day	1.9	6.2	24
pH	7.9±0.1	7.9±0.1	8.0±0.1
COD_T (g/L)	32.3±1.7	32.6±1.4	31.9±1.2
VS (g/L)	23.7±1.7	24.2±1.5	24.9±0.8
COD_{VFA} (mg/L)	0	0	0

and would waste energy. At 20 days HRT, recirculation rate did not affect reactor performance. This must be due to the combination of low solids content in feed animal slurry and the long HRT, which requires minimal mixing for anaerobic digestion.

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The authors have declared no conflict of interest.

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