Journal of Engineering Science and Technology
Special Issue on WRICET2016, December (2018) 78 - 85

A NOVEL OSCILLATORY FLOW BIOREACTOR FOR A POTENTIALLY HIGHER BIOMETHANE GENERATION AND SUSTAINABLE CATTLE MANURE TREATMENT

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Abstract

Anaerobic digestion has been increasingly used for animal manure treatment in recent times, because it offers environmentally sustainable solutions that minimize the impact from livestock waste emissions. However, the conventional lab scale bioreactor commonly used for the anaerobic digestion of animal manure, longer hydraulic retention time and imperfect mixing, deteriorate both the bioreactor stability and biogas production. In this study, a novel oscillatory flow bioreactor (OFBR) with simultaneous provision of good global mixing and plug flow performance was employed. The process performance of methane yield from cattle manure was investigated, and it has been shown that the rate of methane production was higher in the OFBR than the conventional lab scale bioreactor. Hence, adopting the OFBR for animal manure treatment could possibly assist in establishing sustainable and eco-friendly sound agricultural practices in the livestock production systems and integrated farms.

Keywords: Biogas production, Lab scale bioreactor, Methane production, Oscillatory flow bioreactor.

1. Introduction

Global concerns over sustainability of fossil fuels and environmental issues have stimulated worldwide research and development of renewable energy sources for fuel and energy production. Waste biomass is the most abundant organic material, which can be converted to many forms of biofuel; hence, it is a promising feedstock for bioenergy production [1]. Bioreactors are promising technology widely researched and used for decades for sustainable energy production from waste biomass [2]. A bioreactor converts biomass waste via anaerobic digestion into biogas, which comprises about 55-65% methane [3]. To sustain an anaerobic digestion in a bioreactor, the biomass must be mixed adequately; existing methods are mechanical stirring, liquid recirculation and gas recirculation [4]. Recent developments in mixing technology has developed a new way of mixing substrates by introducing an oscillatory motion to replace the conventional mechanical agitation or an air bubble displacement [5]. This mixing is referred to as oscillatory flow mixing (OFM), which relatively provides good mixing and a range of specific process enhancements, such as improved mass transfer, heat transfer, and narrow residence time distribution [6, 7].

This study reports a novel oscillatory flow bioreactor (OFBR) for an anaerobic digestion of cattle manure. In addition, a profound comparison between the OFBR and conventional lab scale bioreactor for the anaerobic digestion of cattle manure, considering the process parameters was made in the present work. The aim of the work was to examine the efficiency, stability and sustainability of the cattle manure anaerobic digestion treatment in the OFBR and lab scale bioreactor.

2. Materials and Methods

2.1. Substrate and inoculum

Cattle manure was collected from a livestock farm located at *Taman Pertanian Universiti* (TPU) on the Universiti Putra Malaysia campus in Serdang, Selangor, Malaysia. Palm oil mill effluent (POME), used as the inoculum, was collected from an anaerobic pond of the Seri Ulu Langat Palm Oil Mill Sdn. Bhd., Dengkil, Malaysia. Cattle manure was mixed 1:1 with water, filtered through a screen (0.5 cm × 0.5 cm), and stored at 4°C for further use, while the inoculum was stored at 4°C until use. The characteristics of the cattle manure and the inoculum are given in Table 1. All samples were analysed in triplicate, and the average of three measurements are given.

2.2. Oscillatory flow bioreactor (OFBR) design and operation

The OFBR for this study was a jacketed stainless steel column (98 mm inner diameter, 146 mm external diameter, 732 mm length, 5.8 L total volume), fitted with plate baffles surrounded by a jacket through which water circulated at 53°C (Fig. 1). The column was mounted on a hydraulic pulsation unit that provided the mixing by substrate oscillation (amplitude = 20mm, and frequency = 2 Hz) at the base of the tube. The OFBR contains the pH sensors, sampling ports, inlets and effluents collectors. In this experiment, the hydraulic retention time (HRT) was kept constant at 18 days by varying the loading rate between 1.3 and 3.3 g VS/L/day.

Table 1. Properties of the cattle manure slurry and POME inoculum used as substrate.

Feed	Parameters	Units	Values
Cattle manure	pH	-	7.1
	Total solids (TS)	mg/L	121
	Volatile solids (VS)	mg/L	91.3
	%TS	% weight	11.7
	%VS	% TS	84.3
	Ammonia-Nitrogen	mg/L	2733
	COD	mg/L	2755
	Alkalinity	mg $CaCO_3$/L	31
	Acetate	mg/L	639.4
	Propionate	mg/L	120.5
	Butyrate	mg/L	70.4
	Total volatile fatty acid	mg/L	880.3
[cont.]			
POME	pH	-	4.2
	Total suspended solids	mg/L	16,700
	Total volatile solids	mg/L	31,300
	COD	mg/L	51,560
	NH_3-N	mg/L	51

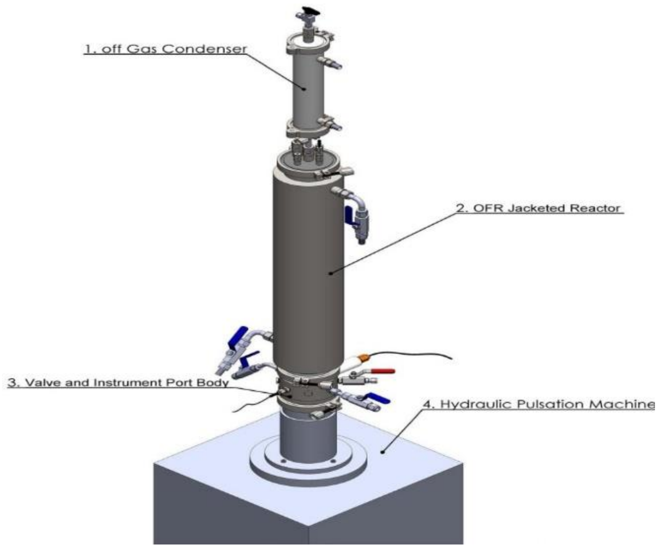

Fig. 1. Schematic of an OFBR system.

2.3. Lab scale bioreactor operation

The lab-scale experiment was carried out using a 10 L capacity jacketed fermenter (Biostat B, Sartorius, Germany) made from a glass vessel with a stainless steel cover. The content of the digester were mixed by an electric motor with four propellers, continuously rotating at 150 rpm (Fig. 2). The bioreactor was heated by circulating water from a thermostatically controlled heater through a water jacket surrounding the bioreactor at 53°C. The reactor is equipped with pH, sampling port and a temperature controller. In this study, the bioreactor was operated as batch and in semi-continuous mode. The substrate at batch operation was loaded into the bioreactor and digestion was carried out for 10 days. Subsequently, the semi-continuous operation was started at day 11 maintained at constant HRT of 20 days at OLR range between 1.7 and 3.63 g VS/L/day.

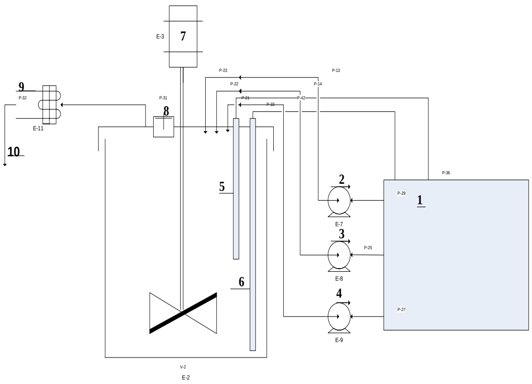

Fig. 2. Schematic diagram of the lab scale bioreactor; 1. Control unit. 2. Acid pump. 3. Base pump. 4. Antifoam pump. 5. pH probe. 6. Temperature controller. 7. Electric motor. 8. Sampling port. 9. Condenser. 10. Off to gas bag.

2.4. Analytical methods

Total solids (TS), volatile solids (VS), chemical oxygen demand (COD), alkalinity and ammonia nitrogen (NH_3-N) were measured according to the Standard Methods [8]. VFAs were measured by gas chromatography (Agilent, 7890N) with a flame ionization detector and a capillary column (Supelco SP 2560 100 m, inner diameter 0.25 mm, film 0.2 µm). The oven was programmed to increase from 150°C which was held for 2 min, to 158°C at 1°C/min and held for 28 min, and then arose up to 220°C at 1°C/min and held for 20 min. The carrier gas used was nitrogen at 1.2 mL/min. The injector and detector temperatures were set to 250°C and 270°C, respectively. Biogas composition (CH_4) was quantified by the gas chromatography (Hewlett Packard 6890N) equipped with a thermal conductivity detector and an HP Molesieve capillary column of 30 m length x 0.5 mm ID x 40 µm film thickness (P/N 19095P). The gas carrier was argon at 20 mL/min. The oven temperature was kept constant at 70°C.

3. Results and Discussions

The reactor performance during the anaerobic digestion of cattle manure in the OFBR and lab scale operation is summarized in Table 2. The analysis of biogas and methane production for the anaerobic digestion indicated that there were major differences among the bioreactors tested. The results for OFBR are better than those obtained from the lab scale bioreactor.

Table 2. Bioreactor performances.

Parameter, unit		OFBR			Lab scale bioreactor	
HRT (days)		18			20	
OLR (g VS/L/d)	1.3	2.4	3.3	1.7	2.42	3.63
Feed TS (%)	9.2	8.6	8.1	-	-	-
VS removal (%)	46	52	49	58.6	48.4	38.2
COD removal (%)	50	61.8	49.6	33.3	41.2	39.4
Biogas production rate (L/L/d)	3.6	5.2	4.7	3.1	1.8	1.2
Biogas yield (L/g VS added)	0.5	0.57	0.35	0.346	0.221	0.114
Methane production rate (L/L/d)	2.1	3.13	2.3	1.6	0.9	0.5
Methane yield (L/g VS added)	0.28	0.34	0.17	0.19	0.11	0.05
CH_4 (%)	56.3	60.3	49.1	52	50	45
Acetate (mg/L)	98	94	219	221	325	413
Propionate (mg/L)	23	31	56	76	95	118
Butyrate (mg/L)	63	41	78	93	138	341
TVFA (mg/L)	209	238	434	416	645	967
pH	7.3	7.0	7.4	7.3	7.4	7.5
NH_3-N (mg/L)	2861	1234	1178	2680	2742	2812

The overall average biogas production rate at initial OLR of 1.3 and 2.4 g VS/L/day varied between 3.6 and 5.2 L/L/day, respectively. However, further increase in the OLR value to 3.3 g VS/L/day, decreased the biogas production to 4.7 L/L/day. High specific methane yields of 0.34 L/g VS added were obtained for the OFBR operation at OLR of 2.4 g VS/L/day. The data of the OFBR digestion may also be compared with previous work. Nasir et al. [9] have also reported similar range (0.1 to 0.37 L/g VS added) of methane yield for the cattle manure anaerobic digestion in various bioreactors. However, the highest methane yield achieved in the lab scale bioreactor of 0.19 L/g VS added, which was by far lower than that presented in the OFBR study (Table 2). Results indicate that the methane generation was faster and to higher level (50% methane by day seven in the OFBR system when compared with the conventional lab scale bioreactor, with achievement of 40% by day fifteen). The overall average of methane yield in the biogas was in the range of 49 to 60% at OLR of 1.3 to 3.3 g VS/L/day (Table 2) in the OFBR. Also, it was observed that increasing the OLR from 2.4 to 3.3 g VS/L/day, decreased the methane proportion in the biogas to 49 %. This is probably due to the CO_2 composition in the biogas which was observed to be higher in the longer OLRs experiment (up to 45%). In addition, it could be attributed to over loading. Percentage of methane in the biogas obtained in the lab scale study (average of 55%) is slightly lower than that of the OFBR as can be seen in Table 2.

In the OFBR, the VS removal efficiency during variation of the OLR was between 46-52% (Table 2). The highest VS removal of 52% was at OLR of 2.4 g VS/L/day, whereas, when the OLR was further increased to 3.3 and 5.1 g VS/L/day, the VS removal efficiency decreased significantly. In the lab scale bioreactor (Table 2) the VS removal efficiency was averagely 58.6% at the end of the study. During the OFBR operation, with every increase of OLR above 2.4 g VS/L/day, propionic acid accumulated, depicting that the acetogenic stage reached its maximal degradation limit. Although, the lab scale bioreactor reactor tended to accumulate acetic acid but the TVFA concentration did not cause notable dynamic effects on the anaerobic process. Published reports on the semi-continuous anaerobic digestion of animal manure using the OFBR were not found for further comparison of these results in this study. However, comparing these results with the previous results (Table 3) on the anaerobic digestion of manure using high rate bioreactors such as the plug flow reactor (PFR), anaerobic sequencing batch reactor (ASBR), up-flow anaerobic sludge blanket (UASB) or induced blanket reactor (IBR), the biogas and methane yield achieved in the novel OFBR is substantially high. This significant quantity of biogas is the result of an efficient novel oscillatory flow mixing (OFM) and effective inoculum (POME) capable of degrading the organic content present in the manure.

Table 3. Performance comparison between various high rate bioreactors and the OFBR.

Substrate	Reactor	OLR (g VS/L/d)	HRT (day)	%COD / VS removal	CH_4 yield (L/g VS added)	Ref.
Dilute dairy waste water	UASB, UAF	0.117-1.3	18.8-2	74, 79% COD removal (UASB, UAF)	0.222, 0.241 (UASB, UAF)	[10]
Cattle manure	UASB	3.68-8.63	5.3-16	36.2-69.7% COD	0.2-0.39	[11]
Dairy manure	2-stage ASBR	6	3	22% VS	0.1	[12]
Cattle manure	SBR	4-6	21	31.2-45% VS	0.124-0.228	[13]
Cattle manure	PSBR	3-5	21	NR	0.161-0.262	[14]
Dairy manure	UASB	1.5-3.7	14	58-69% COD	NR	[15]
Dairy manure	Novel AHR	7.3	15	59-68% VS; 48-63% COD	0.191	[16]
Cattle manure	OFBR	1.3-3.3	18	46-52% VS; 44-62% COD	0.17-0.34	This study

Where, UASB; up-flow anaerobic sludge blanket, UAF; up-flow anaerobic filter, SBR; sequencing batch reactor, PSBR; psychrophilic sequencing batch reactor, AHR; anaerobic hybrid reactor, NR; not reported

The environmental impacts of the OFBR and the lab scale system in terms of the contribution to the reduction of global warming is evident that the higher yield and operational reliability achieved by the OFBR offer enhanced environmental performance when compared with the lab scale digester. It was reported by Whiting and Azapagic [17] and Levlin [18] that the maximum biogas production will give best opportunities to counteract global warming. Hence, it is apparent that for anaerobic digestion of cattle manure, the biogas yield obtained by OFBR is the most sustainable when compared with the biogas yield obtained by the lab scale digester. Hence, adopting the OFBR on an integrated animal production in the oil palm plantation in Malaysia could possibly help producers adopt sustainable and eco-friendly sound agricultural practices in livestock production systems and integrated farms. However, it is important to further study possible technical and economic sustainability for the OFBR.

4. Conclusion

In recent times, anaerobic digestion has been employed by livestock and dairy producers as a means of controlling odorous emissions which contribute to global warming. The benefits of the novel OFBR over the conventional lab scale system for methane generation are obvious. For anaerobic digestion of the cattle manure in the lab scale bioreactor and OFBR, the results indicate that the biogas production rate as L/L/day was higher in the OFBR than the lab scale reactor. It is also noted that the methane content in the biogas and consequently the specific methane production is higher for the latter case. In general, it can be attributed that this higher efficiency in the semi-continuous OFBR to the oscillatory flow mixing effect by the dilution of available toxic materials. The application of this novel technological advancement to enhance biogas yield and prepare for a future climate change is an attractive sustainable alternative to the traditional digesters. Hence, this alternative technology is appropriate for biogas production as reliable and sustainable energy and perhaps ensuring a sustainable development path as articulated in the 2030 Agenda.

Acknowledgement

The authors would like to thank Universiti Putra Malaysia for the financial assistance and facilities, and *Taman Pertanian Universiti* for the feedstock supply.

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