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Influence of intermittent minimal mixing intensity on high-solids anaerobic digestion energy efficiency of dairy manure in a pilot-scale stirred tank digester

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Abstract
The influence of intermittent minimal mixing intensity on high-solids anaerobic digestion energy efficiency of dairy manure was investigated in a pilot-scale anaerobic stirred tank digester operated under mesophilic temperature conditions. A non-mixed experiment was also investigated. Three mixing intensities were investigated; 50, 100 and 150 rpm mixed only once during feeding for a constant mixing time of 5 minutes. The volatile solids concentration ranged from 105.74 to 135 kg m^{-3}, with an organic loading rate varying from 3.5 to 4.5 kg VS m^{-3} d^{-1} for a 30-day hydraulic retention time. The results of the methane yield and specific methane production rate show that the 100 rpm performed better than the 50 rpm which also performed better than the 150 rpm mixing intensity. This research confirms that there exists a mixing intensity threshold for every anaerobic digestion setup and above which increasing the mixing intensity is a waste of energy and does not increase methane production but rather may reduce it. The results of the net energy production in kilowatt hours confirms that the 100 rpm is the economical speed, followed by 50 and 150 rpm. A high mixing intensity is not beneficial to increase methane production but rather waste energy used for mixing and should be avoided. Mixing intensity within the ranges of 50 to 100 rpm is therefore ideal for optimum methane production. Using the net energy production is the best criteria in determining the mixing mode, mixing intensity, mixing time and mixing interval for every anaerobic digestion operating plan.

Keywords: High-solids anaerobic digestion; Energy efficiency; Net energy production; Optimum methane production; Intermittent minimal mixing intensity; Optimum mixing.

1. Introduction

Anaerobic digestion (AD) is a well-known technology for converting organic biodegradable waste into biogas [1-7]. The biogas produced consists mainly of about 55% to 80% methane (CH_4) and about 20% to 45% carbon dioxide (CO_2). Methane is the primary constituent of natural gas and therefore an important renewable energy source. Methane is also a greenhouse gas that is approximately 34 times more effective in trapping heat in the atmosphere than carbon dioxide (CO_2). Anaerobic digestion technology is therefore used to capture and utilize the methane which provides an economic benefit as a source of renewable energy and bio-fertilizer as well as environmental benefits by reducing greenhouse gas, pollution of water bodies and odor emissions. Anaerobic digestion technology is being utilized in the digestion of municipal wastewater solids (MWS), livestock manure, food waste, high strength industrial wastewater and residuals, fats, oils and grease (FOG), the organic fraction of municipal waste solids (OFMWS) and various organic waste streams into biogas [1-11].

AD systems can be classified mainly as low solids anaerobic digestion (LSAD) and high-solids anaerobic digestion (HSAD) [3, 4, 12, 13]. HSAD ($9\% \leq TS \leq 40\%$) is gaining interest due to its potential to increase the energy efficiency of manure management. It also reduces the cost of additional water and the operational cost needed for dilution. Dilution reduces the net energy efficiency of manure treatment [14]. A HSAD system can process more manure per unit volume than a conventional low solids anaerobic digestion system. The size of a digester is reduced compared to the larger size for a diluted solids digester, reducing the capital cost. High volatile solids (VS) digestion at an un-inhibited organic loading rate (OLR) under steady state operation produces more methane than a diluted low solids digestion system. Methane yield and production rate corresponds to the concentration of the VS in the manure. For a given VS concentration and hydraulic retention time (HRT), the maximum methane yield is an important parameter to determine the specific methane production rate. The specific methane production rate and the HRT are important variables in the design and optimum operation of anaerobic digesters. The OLR is therefore dependent of the HRT. HSAD therefore has an advantage of reduced capital and operating costs because of the increased solids loading and could achieve a higher volumetric biogas production rate [3, 4, 9, 13, 15-24]. Therefore, for an anaerobic digester system to be economical in its operation, a high VS concentration of the substrate is an important design consideration. However, the rheological properties of slurries with high total solids (TS) and high VS concentration causes mixing problems either by natural phenomena or with available mixing methods which can reduce the methane yield or cause a total failure of the system due to poor mixing resulting in microorganisms not in active contact with substrates. High power requirement for HSAD is reported with conventional mechanical mixing devices due to the high viscosity requiring higher rotational speeds. It is estimated that the energy demand for mixing in a full-scale digester varies from 8% to 58% of the total energy demand [25-28]. The variations in the energy efficiency are attributed to the substrate type, TS, tank geometries, mixing types and their orientations and mixing operational mode [20, 29]. Foaming and scum formation, caused by inhibition due to the high solids loading and mixing performance challenges are reported which can reduce the anaerobic digestion efficiency and cause eventual digestion failure [13, 19-21, 23]. Mixing strategies developed to break up any floating mats on the digester and re-suspend any settled solids and to improve AD efficiency is necessary for long-term operation of a digester.

The biological processes in the conversion of complex organic matter into biogas involves four known sequential metabolic stages mediated by a consortium of microorganisms. The four sequential stages are: hydrolysis, acidogenesis, acetogenesis and methanogenesis [30]. Generally, the AD process mainly depends on the feed characteristics, the feeding pattern, pH, temperature, redox potential, HRT, solids retention time (SRT) and mixing inside the digester [30-32]. The AD process and performance efficiency are influenced by the proximity of the microorganisms to the available substrates and nutrients, uniform operating temperature and pH, HRT/SRT and the distribution of metabolic waste which are all influenced by mixing [15, 26, 28, 29, 32-37]. Mixing is therefore a physical process that influences the AD process. Stirred tank digesters are designed to provide external physical mixing inside the digesters. The main purpose of mixing is to achieve homogeneity in the fluid mixture and provide an equal platform for the anaerobes.

The economics of AD can be improved to maximize energy produced per unit substrate treated and the quality of the digestate while minimizing the capital and operational costs [28, 29, 32, 35, 38]. Economically, optimized intermittent mixing is reported to reduce the energy demand and maintenance cost as well as improve the biogas production compared to the continuous mixing mode of a continuous stirred-tank reactor (CSTR) [25, 26, 28, 29, 32, 33, 35, 36, 39]. Ideally, mixing must coincide with feeding to homogenize the fresh feed introduced to provide intimate contact between the bacteria, bacterial enzymes, and their substrate and to provide an equal platform for the anaerobes. Therefore, in intermittent mixing the mixing should coincide with feeding to distribute the feed and then mixed occasionally between feedings especially for daily batch-fed or intermittent feeding modes [22, 26, 29, 32, 33]. Kariyama et al. [32] concluded that there is no motivation to continue to operate stirred tank anaerobic digesters as CSTRs if AD energy efficiency is to be improved. AD energy production efficiency can be achieved with optimized intermittent mixing. They concluded that intermittent minimal mixing is enough to maintain the process and performance efficiencies of AD in daily batch-fed digesters producing methane (CH_4).

Most research on the influence of mixing on AD in stirred tank digesters focuses on the process and performance efficiency without an assessment of the mixing energy input and the energy output from the CH_4 produced. Since mixing energy input influences the AD process and performance efficiency, evaluation of the influence of mixing on AD efficiency should include the net energy production efficiency which is the focus of this paper. This paper investigates the influence of intermittent minimal mixing intensity on HSAD of dairy manure in a pilot-scale stirred tank digester with the aim of minimizing the energy used for mixing while maximizing the energy output from the methane produced.

2. Materials and Methods

2.1. The experimental set-up

The pilot-scale digester with total volume of 1.63 m^3 was constructed by a Chinese bioengineering construction firm. Figure 1 and 2 shows a picture and a 2D sketch of the pilot-scale stirred tank digester setup.

Figure 1. The pilot-scale digester setup with manure cold storage basin at the right hand side.

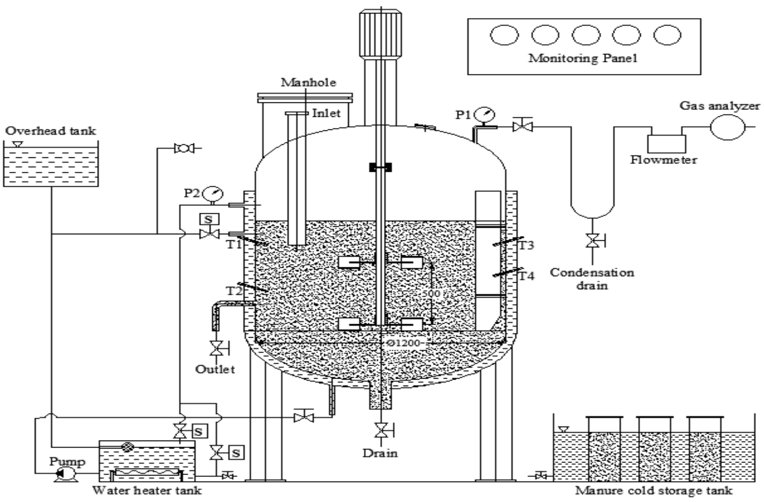

Figure 2. The 2D sketch of the pilot-scale stirred tank digester setup.

Measurement of the digester operating temperature and the pH were continuous and monitored and controlled by the computerized panel. Five temperature probes were installed at different locations to monitor the digester operating temperature. The average operating temperature of the digester was provided by three of these probes at different locations and heights. The heating of the digester was automated and controlled by the computerized monitoring panel to regulate hot water from the water heater tank and cold water flowing through the insulated water jacket to maintain the set temperature. The temperature was set at a mesophilic temperature of 35°C with an accuracy of ±0.30°C and the pH was set at 7.0 with an accuracy of ±0.10. An alkali solution was connected to a peristaltic pump and controlled by the computerized system to control the pH to the set value. The rotational speed of the impeller was also controlled by the computerized panel. The daily biogas volume was measured manually using a gas flow meter (Rongxin, RX02-G1.6) with a maximum discharge of 2.5 m^3 h^{-1} and minimum of 0.016 m^3 h^{-1} and maximum pressure of 50 kPa. The methane content in % vol/vol was measured using GASTIGER 2000. The effluent and samples for analysis were taken at the side discharge outlet while the bottom drain was opened once a month to remove settled deposits. Measurement of the TS and VS were done according to the APHA Standard Methods [40].

2.2. Dairy cattle manure

Dairy cattle manure including urine for running the digester was collected in 50 L drums from a dairy farm in Zhenjiang, China several kilometers from the pilot-scale anaerobic digester plant. The manure was frequently scraped mechanically by alley scrapers pulled by chains into a gutter. The manure to be digested was taken from the gutter and was assumed to be at most a day old since the manure removal system was frequently operated. The manure was taken from the same section of the barn to minimize variations in the manure characteristics. The manure collected was placed in a cold storage basin to minimize microbial activities during storage for at most two weeks. The target storage temperature was 4°C, however, this was difficult to achieve, but the daily influent temperature was below 10°C which did not affect the daily methane production because of temperature shocks and the slow methanogens growth.

2.3. Inoculum for the startup process

The experiment started with seeding of the digester. Fresh manure from the dairy farm was collected and stored in a drum for 4 days under ambient temperature to develop into inoculum for seeding the digester for the startup process. Due to the fact that anaerobic microorganisms are naturally present in cattle manure, the manure on the fourth day was observed to be swollen due to fermentation, an indication that anaerobic microorganisms were present in the manure collected. Inoculum from a wastewater sludge treatment anaerobic digester plant in Zhenjiang was also collected and added to the developed inoculum for seeding the digester. Fresh dewatered digested sludge was obtained from the wastewater treatment anaerobic digester plant and mixed with water and allowed to ferment under ambient condition for four days soaking and dissolving the lumps of solid and to activate the microorganisms before putting them into the digester. These steps were taken to provide enough seeding of the digester to decrease the startup time. Seeding using inoculum has been reported by many researchers to decrease the startup time [15, 41, 42]. The ratio and type of inoculum added is important to speed up the startup process and also to introduce new microorganisms to enhance biogas production [41-43]. The target inoculum/substrate ratio was 10/90 for the startup period [15]. The inoculum prepared from the fresh dewatered sludge was not fully developed before introducing it into the digester due to the fact that the necessary conditions were not provided to accelerate microbial growth. Wastewater anaerobic digester sludge is reported to contain a much higher level of aceticlastic methanogens compared to cattle manure [41, 42, 44-46]. Therefore, using inoculum from anaerobically digested wastewater sludge could create diversity in the microbial community and increase biogas and methane production.

Fresh dairy manure (460.5 kg) was added to the inoculum and mixed to homogenize the contents. Due to a failure of the heating system, the digester operated under ambient temperatures for two days. When the heating system was running more fresh manure was added and gently mixed to homogenize the mixture. This brought the total substrates for the batch startup process to 965.75 kg for 30 days digestion time. The TS of the mixture was 15.61%±0.55% and the VS was 82% of the TS with pH of 7.15. The temperature which is automatically controlled was set to 35°C. For the first few days of the startup process, no additional mixing was performed to allow for initiation and development of the microorganisms [26, 47, 48]. Mixing at 100 rpm was initiated once a day for 5 minutes only when adding alkaline solution to control the pH.

2.4. Non-mixed experiment

The non-mixed experiment started day 34 of the digestion process to investigate the effect of non-mixing on AD process. The pilot-scale digester working volume was 1 m^3 for the non-mixed experiment, operated under mesophilic condition (35°C ±3°C), 30-day HRT, VS concentration of 124.4 kg VS m^{-3} and average organic loading rate (OLR) of 4.1 kg VS m^{-3} d^{-1}. The feeding mode was semi-continuous with 33 kg of digester content discharged once daily through the side discharge outlet before feeding and the same amount fed manually once daily through the inlet pipe at the top.

2.5. Effect of mixing intensity

The effect of mixing intensity on the methane yield and the specific methane production rate was investigated. The pilot-scale digester operated under the same conditions as the non-mixed, however, due to the variability in the manure, the average OLR ranged from 3.8 to 4.1 kg VS m^{-3} d^{-1}. Intermittent minimal mixing at three mixing intensities with rotational speeds of 50, 100 and 150 rpm were investigated. The digester was mixed with two disc pitched bladed turbine impellers vertically mounted on a shaft, consisting of six blades each inclined at 45 degrees. A constant mixing time of 5 minutes was set for the three mixing intensities. Mixing was initiated once a day during feeding only. The biogas production and methane percent were recorded daily.

2.6. Effect of change in HRT and OLR

The effect of the HRT and OLR on the biogas and methane production were investigated. The initial 30-day HRT was reduced to 20-day HRT with OLR of 5.9 to 6.4 kg VS m^{-3} d^{-1}. intermittent minimal mixing once a day at 100 rpm was implemented with a mixing time of 5 minutes.

2.7 Data Comparison

The comparison of the influence of the mixing intensities were achieved using Microsoft excel data analysis tool (Microsoft Excel 2013). The influence of the mixing intensities on the methane yield and specific methane production rate were tested for statistical significance with an alpha of 0.05 ($P = 0.05$). The single factor or one-way analysis of variance (ANOVA) was employed. A further test was conducted using the least significant difference (LSD) test. The net energy production in kWh was computed using Microsoft excel. The energy output of the daily CH_4 produced from each mixing intensity was balanced with the energy input for mixing the digester content for the given mixing time. To convert the volume of biogas produced to the equivalent energy in kWhe electricity, the energy in 1 m^3 of natural gas at 95% CH_4 content was taken as 10.5 kWh [49]. The average CH_4 content of the biogas produced for the three mixing treatments is approximately 71%, therefore, 1 m^3 biogas was converted to equivalent of 2.4 kWhe electricity assuming a 30% electrical conversion efficiency for small-scale combined heat and power (CHP) engine. This value is similar to the value presented by Deublein and Steinhauser [50] for a CHP with maximum electrical conversion efficiency of 40%. The mixing energy input was computed by measuring the power consumption from the installed torque meter device mounted on the shaft with a computerized software that measures the torque and the power consumption simultaneously. The power consumption was converted to electrical energy by multiplying by the mixing time. The daily net energy balance was used to choose the economical mixing intensity. The percentage of the energy output to meet the parasitic energy demand was also computed.

3. Results and discussion

3.1. Comparison of the methane yield and specific methane production rate

The results of the daily specific methane production rates at steady state for the different mixing intensities including the non-mixed experiment are presented in Figure 3.

While digesters rarely operate at a steady state condition, it was assumed that steady state is achieved at two OLR turnovers, since the batch process operated at steady state digestion process before the batch-fed experiment. After the batch process, the non-mixed experiment proceeded for more than one HRT to obtain a steady state. The 100 rpm mixing intensity proceeded after the non-mixed for also more than one HRT before changing to 50 rpm and finally 150 rpm. Due to time constraints the 50 rpm and 150 rpm experiments were run for less than one HRT. Once steady state was reached the experiment was run for a few days and discontinued. Figure 4 presents the results of the methane yields. Table 1 presents the results of the average methane yield and specific methane production rate at steady state.

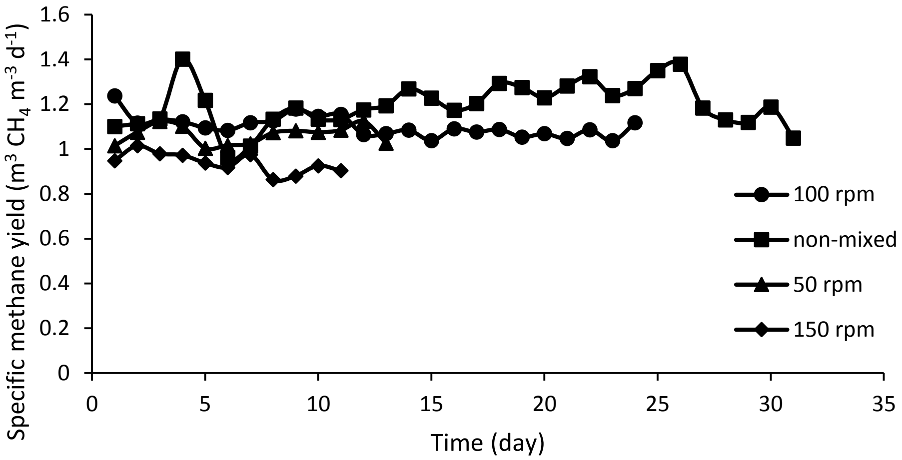

Figure 3. Specific methane production rate at different mixing intensities.

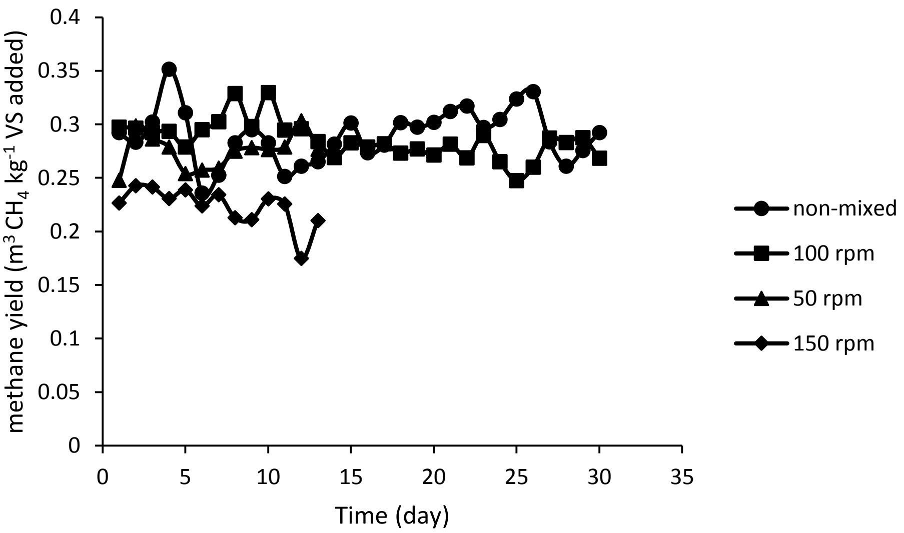

Figure 4. Methane yield for the different mixing intensities.

Table 1. Average methane yield and specific methane production rates for different mixing intensities.

Mixing intensity	**Methane content (%)**	**Methane yield (m^3 CH4/kg VS added)**	**Specific production rate (m3 CH4/m^3 d)**	**HRT (day)**	**VS (kg VS/m^3)**	**OLR (kg VS/m^3 d)**
50 rpm	70.7±0.81	0.28±0.015	1.06±0.042	30	116.33±3.92	3.7 to 4.0
100 rpm	72.4±0.77	0.29±0.016	1.10±0.047	30	114.06±2.97	3.7 to 3.9
150 rpm	70.4±1.09	0.23±0.01	0.94±0.046	30	117.87±2.76	3.8 to 4.0
Non-mixed	70.9±1.68	0.29±0.02	1.21±0.089	30	124.02±6.26	3.9 to 4.3

The results indicate that mixing intensity has an influence on the methane yield and the specific production rate. The ANOVA results showed that methane yield for the three mixing intensities including the non-mixed differ statistically at an alpha level of 0.05 ($P = 7.4E-12$; $F = 35.71$; $F_{crit} = 2.82$; $df = 3, 48$). The

ANOVA results with an alpha level of 0.05 of the methane yield show a statistical difference between three mixing intensities ($P = 7.55E\text{-}13$; $F = 73.07$; $F_{crit} = 3.28$; df = 2, 33). The methane yield of the 100 rpm mixing intensity performed better than the 50 and 150 rpm. The 50 rpm also performed better than the 150 rpm. The results indicate that for high VS digestion, optimum mixing intensity exists for optimum methane yield and production rate. This finding is consistent with findings of previous authors [22, 26, 29, 51, 52]. Kariyama et al. [32], concluded that there exists a mixing intensity threshold for every AD setup above which increasing the mixing intensity is a waste of energy and does not increase CH_4 production but rather may reduce it. Higher mixing intensity above a certain threshold is harmful to microbial consortia and should be avoided. Wiedemann et al. [29] reported that optimum mixing intensity is required to improve AD efficiency. Hughes [22], demonstrated that optimum mixing intensity is required for high biogas production for digesters treating 10.5% TS cow manure under mesophilic conditions at a high OLR. Lindmark et al. [26] reported lower biogas production for continuous mixing at 150 rpm for both high OLR and low OLR compared to mixing at 25 rpm. Lemmer et al. [52] concluded that an optimum mixing intensity is a requirement for every digester operating process in other to achieve optimum biogas and methane production and to improve net energy production efficiency. Sindall et al. [51] showed that there is a mixing intensity threshold above which biogas production decreases. Kaparaju et al. [48] reported that gentle mixing was more beneficial than vigorous continuous mixing. Hoffmann et al. [53] reported that disruption of microbial flocs due to a high mixing intensity during intermittent mixing could cause severe diffusion limitations if the juxtaposed relationship between the syntrophs are disrupted. Rivard et al. [17] concluded that to improve AD efficiency, maximizing the OLR while minimizing the mixing intensities to increase CH_4 production at a minimum cost are preferable. Karim et al. [54] reported a negative impact of high mixing intensity on biogas production with an increasing recirculation rate.

Interestingly, the methane yield of the non-mixed and the 100 rpm were statistically similar. The reason for the similar methane yield could be because of the long HRT of 30 days allowing longer contact time and the benefit of undisturbed closer proximity of the microbial consortia. During non-mixing, the microbial consortia are undisturbed maintaining the juxtaposition that enhances syntrophic relationships which is important to improve the methane yield and specific methane production rate. Mixing within a certain threshold does not disrupt the microbial flocs and juxtaposition and therefore diffusion limitation is not a problem. However, it is important that during feeding the fresh nutrients be distributed uniformly for even contact with the microorganisms. The metabolic wastes are also uniformly distributed to maintain even and optimum operating conditions for optimum microbial activities. Therefore, if a mixing operation must be done it should be done adequately and especially during feeding. Adequate mixing provides a uniform environment for anaerobic bacteria, which is one of the major factors in obtaining maximum digestion [15, 53-57]. Inadequate mixing leads to less contact of the substrates with the microorganisms, reduced methane yield and production. Inadequate mixing inside the digester contributes to digester failure in the long-term [58-60]. This result is in contrast to the report of Vavilin and Angelidaki [47] that reported that uneven mixing can create initiation zones where methanogens can grow and thrive and from there they can then seed the rest of the digester. Digester initiation is important during the startup process, however, since most digester design is based on the daily specific methane production rate which is influenced by the methane yield, adequate mixing at steady state operation during feeding should be preferred to avoid digester failure in the long-term due to accumulation of volatile fatty acids.

Figure 3 and the results presented in Table 1 shows that the specific methane production rate depends not only on the methane yield but also on the OLR and the VS concentration. Although the methane yield of the non-mixed and the 100 rpm mixing intensity were the same, the specific methane production rate of the non-mixed was higher due to the higher VS concentration. The variability in the VS can therefore influence the daily specific methane production rate.

Table 2. The net energy production.

Mixing intensity (rpm)	Daily CH_4 production (m^3)	Equivalent (kWh)	Parasitic energy for mixing (kWh)	Net energy (kWh)	Parasitic energy met by energy produced (%)	MEL (W/m^3)
50	1.06	3.583	0.002	3.581	0.056	24
100	1.10	3.718	0.013	3.705	0.353	157
150	0.94	3.177	0.034	3.143	1.084	409

3.2. Comparison of the net energy production

Figure 5 shows the measured impeller power consumption.

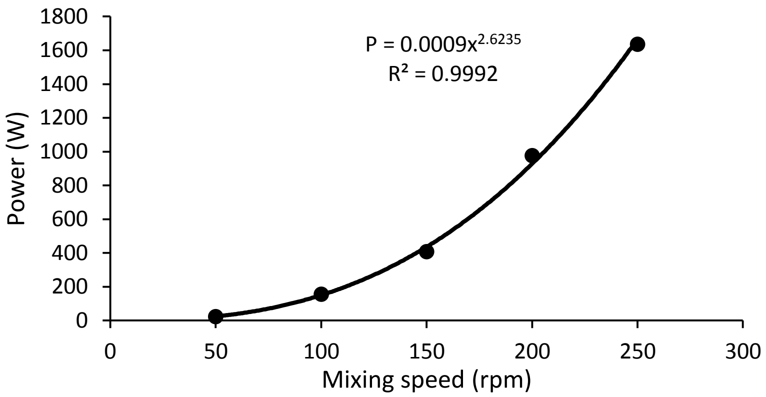

Figure 5. Power consumption curve.

The results show that as the impeller rotational speed increases, the power consumption increases exponentially creating high turbulent mixing in the digester which is not beneficial for microbial activities. Table 2 presents the net energy production.

The computed net energy production shows that the 100 rpm mixing intensity net energy production was higher even though the power consumption was higher than the 50 rpm. The mixing time was set the same (5 minutes) and mixing done once daily only during feeding. The electrical energy consumed was small as shown in Table 2. The equivalent electrical energy derived from the system at 100 rpm could offset the parasitic energy for mixing with a net balance still higher than the 50 rpm system. Generally, only a small proportion of the energy derived from the methane produced was used to satisfy the parasitic energy for mixing. Intermittent minimal mixing at an un-inhibited OLR and strategic management could therefore drastically reduce the mixing energy demand and improve the AD efficiency and the economics of AD. Though the mixing energy level (MEL) for this optimized impeller design is higher than the recommended impellers for HSAD presented by Wu [20] it's better than the conventional four pitched bladed turbine (4PBT) [20, 61]. Ding et al. [61] reported that the optimized impeller generated a better velocity distribution at a lower speed than the conventional 4PBT. This work revealed the fact that intermittent minimal mixing for a batch-fed HSAD is economical and should be preferred.

3.3. The effect of OLR and HRT

The HRT was reduced from the initial 30-day to 20-day HRT and daily loading was adjusted to 50 kg with an OLR ranging from 5.9 to 6.4 kg VS m^{-3} d^{-1}. A week after initiation of the experiment, digestion process instability was experienced causing severe foaming which could not be controlled. The foaming could not be controlled and the experiment was discontinued. The gas flow meter and pipeline were filled with liquid slurry restricting free flow and causing pressure buildup at the digester. During foaming, the digester content was mixed for about 20 minutes to control the foaming before feeding. After feeding the content was mixed for 5 minutes. Feeding was also stopped for some days to ensure that the digester stabilized. All these management strategies proved futile and the experiment was ended after 20 days of its initiation. Our observation shows that overloading should be avoided and that the 20-day HRT is not ideal. Our finding is in agreement with the finding of Hashimoto [62]. Hashimoto [62] reported maximum unstressed OLR of less than 5 kg VS m^{-3} d^{-1} for 128 kg VS m^{-3} at 35°C. When the OLR was 5.1 kg VS m^{-3} d^{-1} digestion stress was experienced. For a 20-day HRT and an OLR of 6.4 kg VS m^{-3} d^{-1} methane yield was only 0.14 m^3 CH_4 kg^{-1} VS added due to digestion stress. They recommended that to maintain a stable digestion process, a lower OLR for high TS and VS must be used. The results confirm the fact that even though mixing influences the methane yield and the specific methane production rate, an appropriate OLR and the other factors that influence the biodegradability of manure are equally or more important. Table 3 gives the ultimate methane yield of cattle manure against the OLR under mesophilic temperature conditions in stirred tank digesters from literature.

Table 3. Ultimate methane yield of cattle manure at mesophilic conditions presented in literature.

T (°C)	VS (kg/m^3)	HRT/DT (days)	OLR (kg VS/m^3 d)	CH_4 yield (m^3/kg VS added)	Cattle manure	authors
35	64.1	15	4.26	0.20	dairy	Converse et al. [64]
35	64.9	10.4	6.22	0.15	dairy	Converse et al. [64]
40	77.7	25	3	0.21	dairy	Mackie and Bryant [65]
40	77.7	13	6	0.18	dairy	Mackie and Bryant [65]
24	77.5	30	2.58	0.10	dairy	Linke, [66]
35	77.5	30	2.58	0. 13	dairy	Linke, [66]
33	45	20	2.25	0.25	dairy	Linke, [66]
33	45	10	4.5	0.20	dairy	Linke, [66]
35	43	15	2.86	0.376	beef	Hashimoto [63]
35	64	15	4.26	0.352	beef	Hashimoto [63]
35	82	15	5.46	0.356	beef	Hashimoto [63]
35	100	15	6.66	0.318	beef	Hashimoto [63]
35	128	15	8.53	0.01	beef	Hashimoto [63]
35	128	25	5.12	0.234	beef	Hashimoto [63]
35	34	16.2	2	0.27	dairy	Karim et al. [18]
35	53	16.2	3.24	0.23	dairy	Karim et al. [18]
35	75	16.2	3.24	0.17	dairy	Karim et al. [18]
35	27	24.4	1.11	0.40	dairy	Karim et al. [18]
35	27	20.5	1.32	0.34	dairy	Karim et al. [67]
35	27	16.1	1.68	0.34	dairy	Karim et al. [67]
35	27	13.8	1.96	0.37	dairy	Karim et al. [67]
35	27	11.3	2.39	0.34	dairy	Karim et al. [67]
35	27	8.1	3.33	0.29	dairy	Karim et al. [67]
35	27	6.9	3.91	0.29	dairy	Karim et al. [67]
35	27	4.6	5.87	0.20	dairy	Karim et al. [67]
34	50	15	3.5	0.241	dairy	Hoffmann et al. [54]
37	45	20	2.3	0.22	dairy	Rico et al. [33]
37	45	10	4.5	0.20	dairy	Rico et al. [33]
38	51.85	42	1.3	0.256	dairy	Normak et al. [68]
38	51.85	25	2	0.291	dairy	Normak et al. [68]
35	130.21	35		0.356	dairy	Jha et al. [20]
35	65.9	30	2.2	0.16	dairy	Nandi et al. [37]
2.5	34.9	30	1.16	0.271	dairy	Chen and Hashimoto [69]
32.5	52.3	30	1.74	0.251	dairy	Chen and Hashimoto [69]
32.5	69.8	30	2.33	0.236	dairy	Chen and Hashimoto [69]
32.5	87.2	30	2.91	0.222	dairy	Chen and Hashimoto [69]

The results indicate that the methane yield and production rate depends more on the VS, OLR and the HRT than the effect of mixing [32]. The biodegradable portion of the organic waste, and how long its stays in the digester in contact with microorganisms determines the methane yield and production rate. Although mixing plays a vital role to ensure that the fresh feed is in contact with the microorganisms within a short time, for longer HRT the effect of mixing is minimal within the mixing intensity threshold. Mixing is therefore more important for a shorter HRT than for a longer HRT. However, a shorter HRT corresponds to a high OLR and therefore the minimum HRT should correspond to the un-inhibited OLR. An inhibited OLR should be avoided in AD. Generally increasing the OLR reduces the methane yield, however, the methane production rate increased. In Table 3, the values of the VS are lower than the values presented in this paper except for values presented by Hashimoto [62] and Jha et al. [18]. The results of Table 1 are comparable to values presented by Hashimoto [62] even though the biodegradability of beef manure was reported higher than dairy manure in their paper. For 128 kg VS m^{-3}, OLR of 5.12 kg VS m^{-3} d and 25-day HRT, the methane yield was 0.243 m^3 CH_4 kg^{-1} VS added which is lower than values presented in this paper for 30-HRT which is to be expected because of the trend presented in Table 3. It should be noted that during the batch experiment, the VS was 128 kg VS m^{-3} similar to Hashimoto [62] and the ultimate methane yield was 0.28 m^3 CH_4 kg^{-1} VS added although foaming was experienced during the digestion process before stabilization. Jha et al. [18] reported higher methane yield for dairy manure with VS concentration of 130 kg VS m^{-3}, batch digestion time (DT) of 35 days. One of the reasons for the high methane yield could be attributed to the high inoculum of 20% used to seed the digester.

The 30-day HRT used in this paper and the values of the methane yield obtained as presented in Table 1 compared to the values provided in Table 3 are promising for HSAD of dairy manure. The management strategy of removing the digestate at the side discharge outlet before feeding and mixing avoids any possible bypass during discharging as reported in continuously stirred tank digesters. Also this operational strategy decouples the HRT and SRT as some of the solids settle at the bottom of the digester during the non-mixed period thereby maintaining a longer SRT in the digester. The digester therefore operates as a high rate digester with improved AD efficiency. The drain at the bottom is opened once a month to remove silts and settled objects. Also the diversity of methanogens are important in improving AD efficiency. Even though, this paper did not investigate the diversity of the methanogens, using inoculum from wastewater treatment anaerobic digester plant could provide a balance between hydrogenotrophic and acetotrophic methanogenesis which is required to improved AD efficiency [32]. While it is important to optimize the mixing intensity, other factors that improve AD efficiency must also be employed for optimum results. Pretreatment is also reported to enhance anaerobic digestion process and performance [4, 63].

Conclusions

Intermittent minimal mixing is enough to maintain the process and performance efficiencies of HSAD in a daily batch-fed digester at an un-inhibited OLR. Mixing once a day at an optimized mixing intensity and mixing time can save approximately 99% of the energy derived from the methane produced. There exists a mixing intensity threshold for every AD setup above which increasing the mixing intensity is a waste of energy and does not increase CH_4 production but rather may reduce it. Though non-mixing experiments have shown high biogas and CH_4 production comparable to the optimized intermittent mixing intensity, for long-term operations of anaerobic stirred tank digesters, mixing is required. Decoupling the HRT and SRT in a stirred tank digester is a management strategy that can improve AD if it does not add to the capital or operational cost. Mixed inoculum with diversity of methanogens could improve optimum methane production.

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