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# Improvement of Biogas Production Efficiency from Dairy Manure by Air-lift System Using Simple Simulation Program and Reactor Operation Approaches

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## Abstract

Anaerobic process has been perceived as a sustainable method for treating and producing biogas from dairy farm. However, some operational problems have regularly been reported. This study was conducted in order to determine the suitable mixing scheme for the modified covered lagoon using air-lift systems to enhance the system efficiency and prevent the pipe clogging problem. Suitable biogas flowrate and installing position for the air-lift system were determined via the flow scheme simulation using ANSYS Student 2019 program. Both biogas flowrates and installation positions were found to significantly affect the mixing regimes and reactor performances. At the suitable biogas flowrate of 20 L/min, reactor contents were properly mixed both in the front and the reaction parts of the reactor. Results from the actual reactor operation using three 8 $m^3$-modified covered lagoons operated at the organic loading rate of 2.0 kg VS/$m^3$-d showed that anaerobic pond installed with the air-lift system in the front part provided better system stability, waste treatment and biogas production efficiencies compared to those obtained from the one with the air-lift system both in the front and the end parts and the control one without any mixing system.

**Keywords :** Anaerobic digestion; Biogas; Air-lift; Dairy manure

## Introduction

Dairy farming contributes substantially to the growth of some agricultural countries. In Thailand, there are approximately 17,837 households associated with dairy farming in different parts of the country. The majority of these farms are small-scales (55%), which mostly employ family members (85%). Milk production amounted to 2,093,412 kg of milk daily in 2009 [1]. However, activities of dairy farms generate a significant amount of waste, especially dairy manure consisting of organics, solids and nutrients. This waste can pollute the environment if it is not appropriately managed. Dairy manure, on the other hand, can be a useful resource for renewable energy production in forms of biogas in anaerobic digestion [2]. Biogas can play an important role in dairy farm activities, e.g. as a fuel to boil milk, produce hot water for disinfection and can also be used to produce electricity for large farms having large amounts of waste [3]. One of the problems utilizing biogas reactors is the low efficiency or even system failure caused by the accumulation of solids in the pipe or openings in the system leading to clogging [4]. This problem is rather common when dairy manure is used as the feedstock as it can contain high amounts of biomass fiber and grits [5, 6]. Alleviation of clogging problems have been reported to be done by combining the mixing system with the biogas reactor as mixing helps to homogenize liquid phase and solids phase throughout the digester.

Many researchers discovered that mixing system rendered better performance for biogas reactor. Wang et al. analyzed the biogas digester fed with cow manure and operated under 3 modes, i.e., unmix, continuous mix (mixing for 15 minutes at 15 minutes interval) and intermediate mixing (mixing for 15 minutes at 45 minutes interval). Methane percentages in biogas obtained from digesters with continuous mixing was significantly higher than those from the unmixed and intermediate mixing [4]. Nandi et al. investigated effects of mixing on the performance of anaerobic reactor digesting cow manure under continuous mixing (mixing at 100 rpm for 5 min at 15 min interval) with propeller, and without mixing. The highest biogas production was also gained from reactor with mixing [7]. Jegede et al. also found that up to 40.6% higher of specific biogas production anaerobic were detected from the Chinese dome digesters treating cow manure and operated as the impeller mixed digesters (STRs) compared to those gained from the unmixed digesters (UMDs) [8]. Mixing patterns also affected reactor performance as Babaei and Shayegan reported that intermittent mixing (15 min on and 30 min off) could improve biogas production by 30–40% compared to continuous and minimal mixing (twice in a batch per day and 30 min each time) when municipal solid waste was used as the feedstock in anaerobic digesters [9]. From previous studies, majority of mixing method investigated in anaerobic digesters were conducted using the propeller. Though it is rather convenient to install, flexible to use and can generate enough mixing intensity for anaerobic digestion, propeller mixing could require high energy and maintenance cost. Moreover, it is not practical for the large-scale anaerobic digester as either numbers or sizes of propeller-driving motors can be the major constrain. Reactor mixing can effectively be done via the air-lift configuration. Air-lift operation is conducted through the installation of pipes below the water level in the reactor. The compressed air or, for anaerobic digesters, biogas produced inside the reactor is pumped through to the pipe at the lower end to push the water up to the height above the water level in reactor, generating particular flow pattern as a loop circulation [10]. The advantages of air-lift is good mixing, low energy requirements, low operation and maintenance cost, low contamination risk and no heat generation [11]. This study aimed to (1) utilize the simple simulation program to assess conditions for air-lift mixing and (2) investigate effects of biogas flow rates and installing positions for air-lift system on biogas production efficiencies of the full-scale modified covered lagoons (MCL) treating dairy manure.

## Methodology

### Substrate

Dairy manure used in this study was obtained from Darunee farm, Doi Lor District, Chiang Mai, Thailand. The fresh manure was stored in a storage tank at ambient temperatures before feeding. Concentrations of Chemical oxygen demand (COD), Total solids (TS) and Volatile solids (VS) were 64,959±3,913 mg/L, 57,863±7,395 mg/L and 48,875±6,919 mg/L, respectively. Temperatures of cow manure was 29.48±1.18 °C. Dairy manure characteristics are shown in Table 1.

**Table 1** Dairy manure characteristics

| **Parameters** | |
|---|---|
| pH | 6.88±0.05 |
| TS (mg/L) | 57,863±7,395 |
| VS (mg/L) | 48,875±6,919 |
| VFA (mg/L$CH_3COOH$) | 13,528±901 |
| Alkalinity (mg/L$CaCO_3$) | 3,869±310 |
| COD (mg/L) | 64,959±3,913 |
| Temperature (°C) | 29.48±1.18 |

## Experimental methods

The experiment was divided into 3 parts. In the first part, the specific methane yield of dairy manure was determined using the biochemical methane potential (BMP) test. The second part was conducted to find the suitable biogas flowrate and installing position for the air-lift system using ANSYS FLUENT (2019, Student Version). In the third part, effects of air-lift systems on the performance of three identical full-scale modified covered lagoon system (MCLs) were investigated. Details of each experiment are explained as follows:

### 1. BMP test

The specific methane yield of dairy manure was determined using the BMP test. This test has been used to characterize various substrates and is an important tool for determine methane potential, biodegradability and phase of digestion [12]. The obtained results were fitted with the modified Gompertz model [13] in order to gain the maximum methane production from this waste.

The BMP test was performed in 1,000 mL glass bottles with working volume of 400 mL under mesophilic conditions. The bottle was added with inoculum (120 mL) and dairy manure (9 mL) to have the inoculum to cow manure ratio of 2:1 by VS. Then distilled water was added to reach the working volume. Alkalinity was adjusted with sodium bicarbonate to reach the pH around 7.0. Each bottle was purged with nitrogen gas for 3 minutes to ensure anaerobic conditions and then sealed with a septum. The controlled experiment (blank) was also prepared using only inoculum. Temperature was maintained at 35±2 °C by keeping each bottle inside the water bath (Memmert WNB 45, Germany). All experiments including blank were done in 3 replicates for a period of 55 days

Biogas production was measured via gas pressure in the bottle using Digital Manometer (DM9200, Obereisesheim, Germany). Each bottle was manually shaken before pressure measurement. When pressure reached approximately 250 mbar, biogas compositions were measured using Multichannel Portable Gas Analyzer (Gas Data, GFM406, Coventry, U.K.). Conversion of bottle pressures into volumes of biogas at standard temperature and pressure was done using Equation (1) [14].

$$V_0^{tr} = \frac{V\,(P - P_w)\,T_0}{P_0\,T} \qquad (1)$$

where $V_0^{tr}$, V, $T_0$, T, $P_w$, $P_0$ and P represent volume of dry gas at standard temperature and, volume of gas as read off (mL), pressure (mL) normal temperature (273 K), temperature of the fermentation gas or ambient space (K), vapor pressure of water as function of temperature of ambient space (hPa), normal pressure (1,013 hPa) and pressure of gas phase at the time of reading (hPa), respectively.

Results from BMP tests were used to create a model for the prediction of methane generated by fitting with the modified Gompertz model (Eq. 2) [13].

$$M = M_0 \times \exp\left\{-\exp\left(\frac{R_m \times e}{M_0}(\lambda - t) + 1\right)\right\} \qquad (2)$$

where M, $M_0$, $R_m$, and λ represent the cumulative methane yield (mL $CH_4$/gVS) at a given time, methane production potential (mL$CH_4$/gVS), maximum methane production rate (mL$CH_4$/gVS-d), and lag phase (d), respectively.

### 2. Reactor mixing regime simulations

Reactor mixing regimes were analyzed by simulating the flow regime inside the 2D reaction tank using ANSYS FLUENT (2019, Student Version). The calculation was undertaken using the numerical method, i.e. the fractional step discretization of the time-dependent incompressible Navier-Stokes equations [15], to find the answer from the governing equations shown in Table 2. The program was set up to find the multiphase equation of each type of phase, i.e., liquid, solids and gas, in the reactor. This relied on the volume of fluid method for calculation and was simulated as the triangle unstructured mesh with approximately 400,000 elements. The set boundary condition of the experiment is shown in Figure 1 and dimensions of the reactor is presented in Figure 2.

**Table 2** Numerical methods to find the answer from the Governing equations

| | Governing equations |
|---|---|
| equations | Incompressible Navier-Stokes equations |
| Transient term | Second order implicit metho |
| Spatial derivatives term | Second order finite volume upwind method |
| Pressure-velocity coupling | Fractional step method |
| Pressure term | PRESTO |

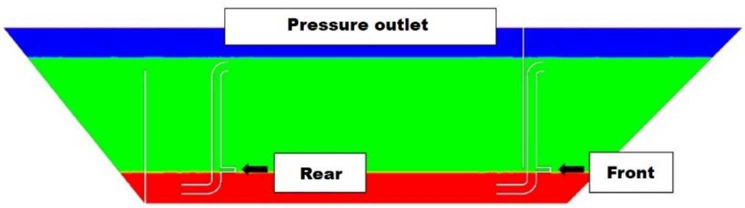



**Figure 1** Boundary condition for simulation (green = liguid; red = solids; blue = gas)

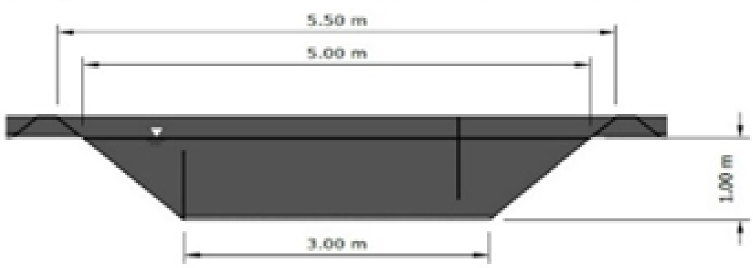



**Figure 2** Dimensions of reactor

Three different biogas flowrates, i.e., 5, 10 and 20 L/min, were simulated when air-lift systems were operated both in the front and rear parts of the reactor (namely Case 1, 2 and 3, respectively). Also mixing pattern was investigated when the air-lift system was operated only in the front part at the biogas flow rate of 20 L/min (Case 4). The initial simulation condition is presented in Table 3.

## 3. Effects of air-lift systems on the performance of MCLs

Effects of air-lift systems on the performance of three identical full-scale MCLs (R1, R2 and R3) were investigated at Darunee farm, Doi Lo District, Chiang Mai, Thailand. Each MCL (Fig 3(a)) had the working volume of 8 $m^3$ and was fed via the feeding pipe located at the front end of the reactor while effluent was overflowed through the effluent pipe installed at the other end of the reactor1 and dimensions of the reactor is presented in Figure 4. The HDPE sheet was used to cover each reactor and biogas was collected via a gas pipe located at the rear part of the reactor. Before feeding, dairy manure was mixed with water at the ratio of 1:1.5 by wt. The reactor was manually fed 3 days/week with amount of dairy manure of 589.5 L. R1 was used as the controlled reactor and operated while the air-lift system was completely turned off (without mixing). R2 was operated with the air-lift system only in the front part was turned on, while in R3 air-lift systems both in the front and rear parts were on. At each location, two pipes were installed and the biogas flowrate was equally divided through these two pipes (Fig 3(b)). All reactors were fed with the real dairy waste under ambient temperatures and operated at the OLR of 2.0 kg VS/$m^3$-d for 112 d, which was equivalent to 3.5 times of the HRT. The air-lift system in R2 and R3 was on for 20 min every one hour [9] and operated at the biogas flowrate of 20 L/min. Dimensions of the reactor is presented in Figure 4.

To monitor the reactor performance, temperature, biogas volume (diaphragm meter; AMPY Gas Meter Model 750, ZETLAND, Australia), biogas composition (multichannel portable gas analyzer version GFM406, Gas Data, Coventry, U.K.) and pH (pH meter; TQC Sheen, WATERPROOF PHTESTR30, Netherlands) were measured at the site three times per week. Samples of effluent were taken on weekly basis and analyzed for chemical oxygen demand (COD), total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), volatile fatty acids (VFA), and alkalinity (ALK) according to the Standard Methods [16].

### 4. Statistical Analysis

The experimental data of all studied reactors were investigated and compared using the one-way analysis of variance (ANOVA) at the confidence level of 95%.

## Results and Discussions

### Potential of biogas production from dairy manure

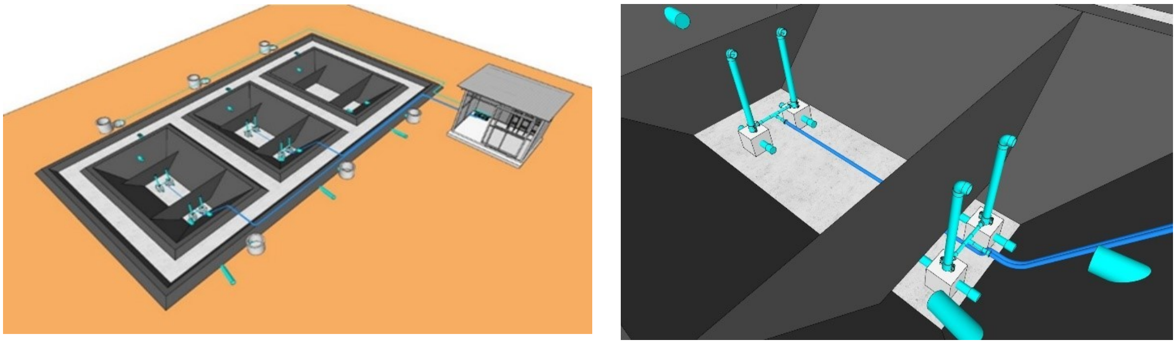
The specific methane production obtained from the modified BMP test was 196 L $CH_4$/kg VS in 55 days of experiment (Fig 5). Results fitted well with the modified Gompertz model ($R^2$ = 0.99) [13] and the total specific methane yield (P) obtained was 316.11 L $CH_4$/kg VS with the lag time ($\lambda$) of 3.50 d (Table 4). These values were in the same range as those reported to gain from dairy manure in previous studies [17].

### Simulations of reactor mixing

Visual mixing images of different phases and velocity magnitudes and directions inside the reactor are shown in Fig 6. For Case 1, it was found that at the end of the simulation period (60 sec), majority of solids (especially at the middle part of the reactor) still settled at the bottom of the reactor which was corresponded with the small velocity magnitude and relatively larger dead zone area (Fig 6(a)). When biogas flowrate was increased to 10 L/min (Case 2), less solids were settled in the middle part of the reactor. However, small velocity magnitude, especially right at the area behind the first baffle wall, was still clearly observed (Fig 6(b)). Mixing at this particular area is crucial as the organic loading at the front of the reactor is high and thorough contact between microorganisms and substrates need to be achieved to avoid low pH profile and imbalance conditions among different microbial group at the latter parts of the reactor. At the biogas flowrate of 20 L/min (Case 3; Fig 6(c)), better mixing in the middle part of the reactor was visually observed. More importantly, velocity vectors behind the first baffle wall area were obviously present with much lesser dead zone area. When only the front part air-lift system was operated at the flowrate of 20 L/min (Case 4; Fig 6(d)), almost all solids were settled in the middle part of the reactor. Yet, thorough mixing was still attained at the front part and considerable velocity vectors are spotted behind the first baffle wall. From these aforementioned results, biogas flowrate of 20 L/min was chosen as the optimum condition for MCL mixing. Operation of the air-lift system at different locations in the reactor was then investigated using the pilot-scale MCLs.

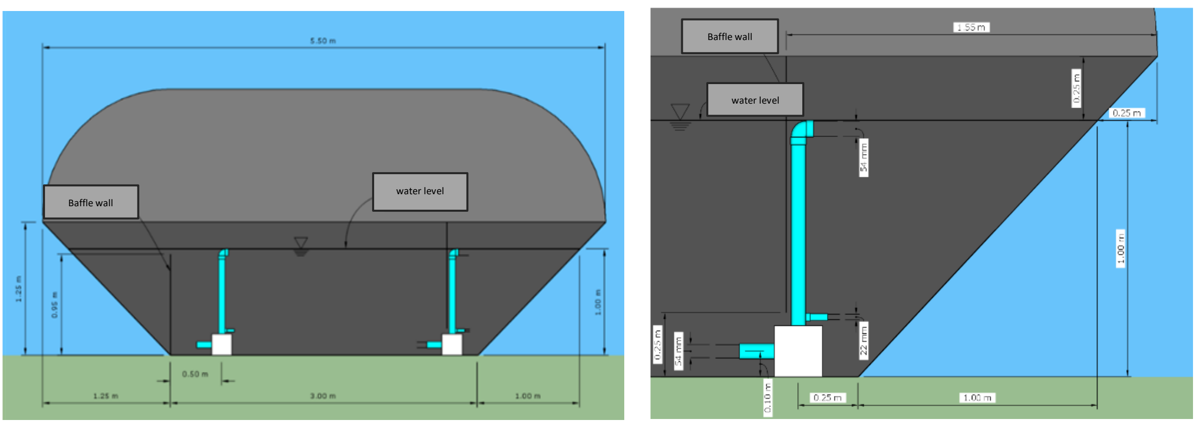
**Table 3** Initial simulation conditions

| Case | Gas flow rate (L/min) | | Position of mixing |
|---|---|---|---|
| | Front | Rear | |
| 1 | 5 | 5 | front and rear |
| 2 | 10 | 10 | front and rear |
| 3 | 20 | 20 | front and rear |
| 4 | 20 | 0 | front |



(a) (b)

**Figure 3** Full-scale MCLs (a) and air- lift system in each MCL (b)




(a) (b)

**Figure 4** Dimensions of MCL (a) and air lift system (b)

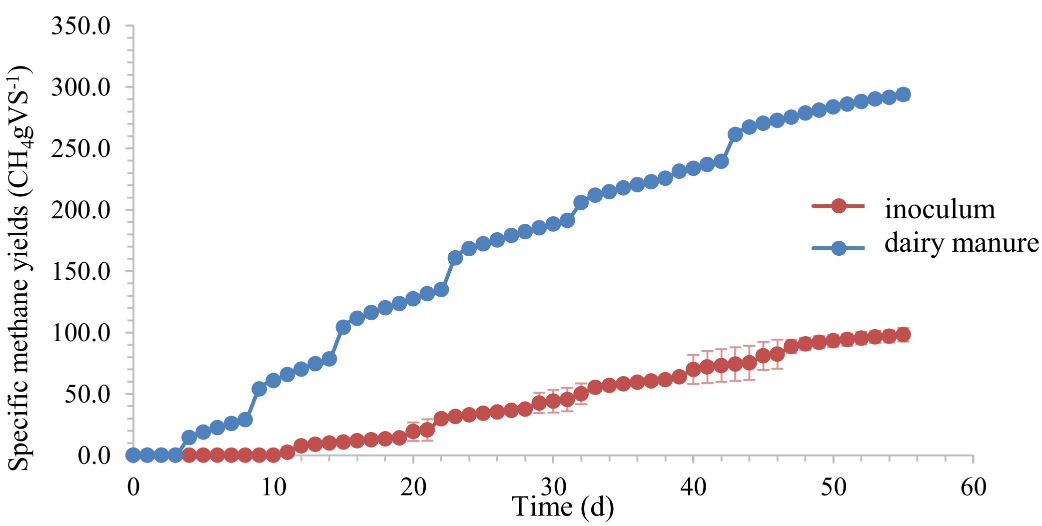
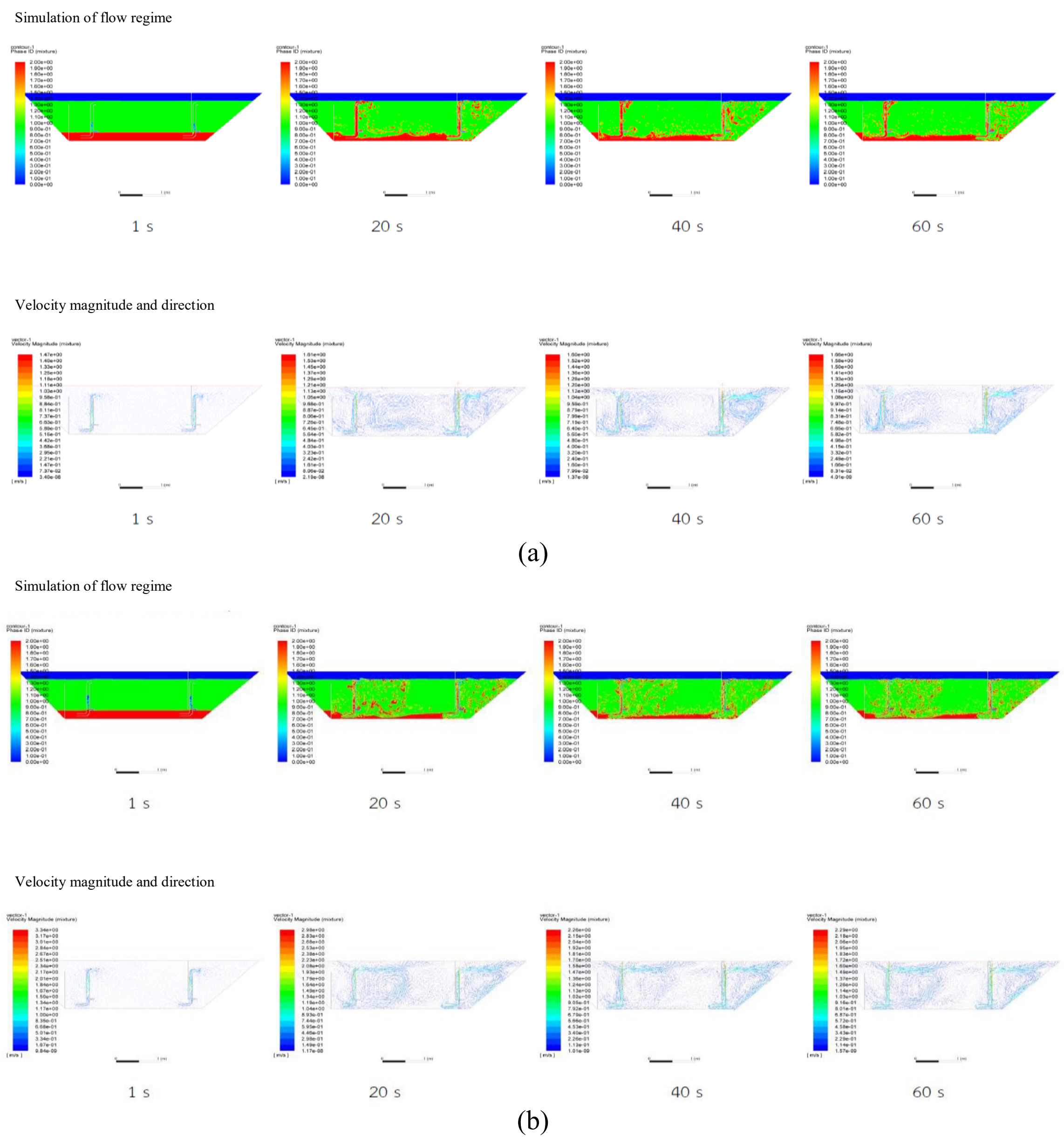
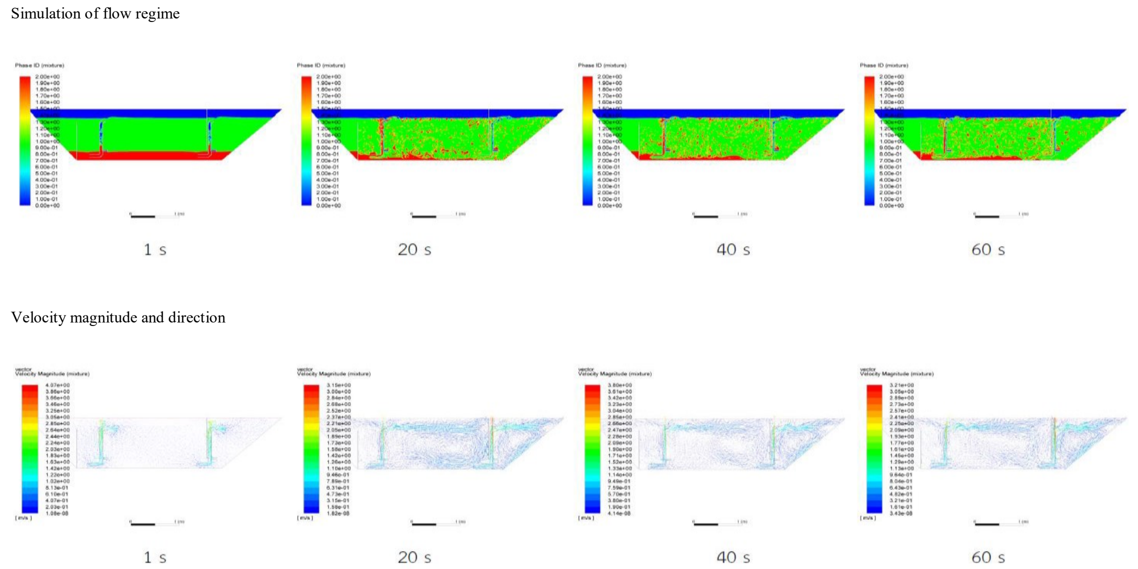



**Figure 5** Results obtained from the BMP

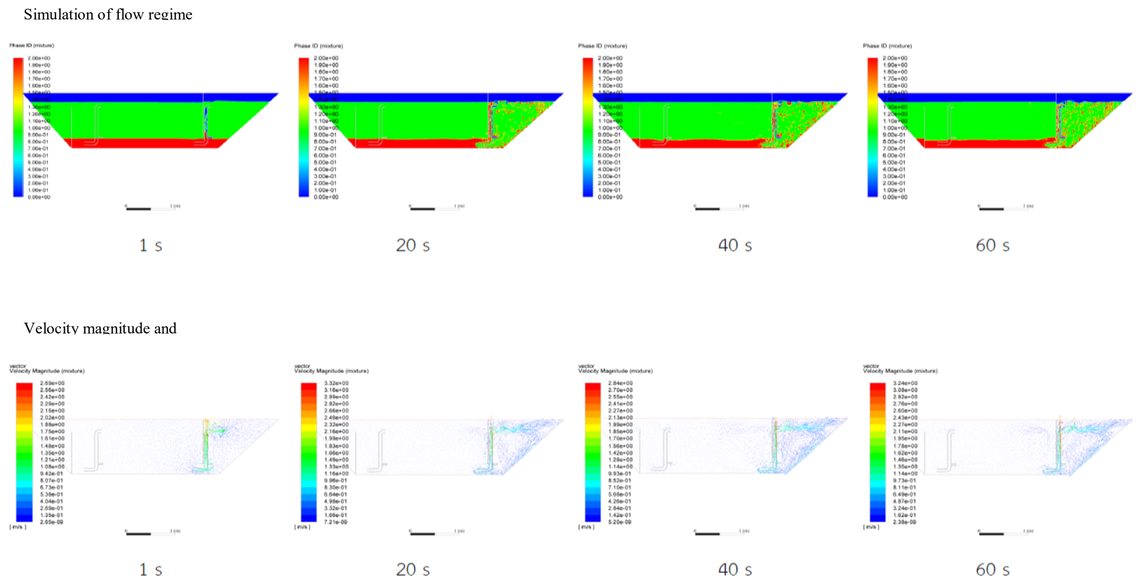
**Table 4** Results obtained from the modified Gompertz model

| Sample | P (ml $CH_4$/g VS) | $R_m$ | λ | $R^2$ |
|---|---|---|---|---|
| Dairy manure | 316.11 | 7.65 | 3.50 | 0.99 |






(c)




(d)

**Figure 6** Simulations of reactor mixing at different biogas flowrates; (a) 5 L/min (Case 1), (b) 10 L/min (Case 2), (C) 20 L/min (Case 3) and (d) 20 L/min (Case 4; the air-lift system was operated only in the front part)

**Effects of air-lift system operations on the performance of MCLs**

Performance of all studied MCLs is presented in Table 4. Effluent pH values of R1, R2 and R3 were 7.31±0.04, 7.22±0.11 and 7.25±0.04, respectively, which were within the optimum range for suitable anaerobic digestion (6.8–7.2; [18]). All reactors were operated under the temperatures of 31.52±0.73, 31.64±0.79, 31.68±0.75 °C for R1, R2 and R3, respectively. These temperatures were in the optimum range of 30–39 °C [19], which was suitable for the growth and function of mesophiles.

**Table 4** Performance of all studied MCLs

| Parameter | Influent | Effluent | | |
|---|---|---|---|---|
| | | R1 | R2 | R3 |
| pH | 6.89±0.11 | 7.31±0.04 | 7.22±0.11 | 7.25±0.04 |
| Temperature (°C) | 29.48±1.18 | 31.52±0.73 | 31.64±0.79 | 31.68±0.75 |
| COD (mg/L) | 57,789±11,420 | 24,487±4,675 | 27,396±8,055 | 31,355±8.899 |
| TS (mg/L) | 57,548±10,276 | 30,073±6,318 | 29,685±8,986 | 35,017±7,089 |
| VS (mg/L) | 48,873±8,744 | 23,244±5,365 | 23,850±7,631 | 27,403±5,522 |
| Alk (mg/L$CaCO_3$) | | 2,915±0.11 | 2,422±631 | 2,522±333 |
| VFA (mg/L$CH_3COOH$) | | 1,419±127 | 970±222 | 998±132 |
| VFA/Alk | | 0.49±0.04 | 0.41±0.04 | 0.40±0.05 |
| $CH_4$(%) | | 54.7±9.1 | 51.6±11.4 | 57.3±4.6 |
| Biogas production (L/day) | | 2,084±356 | 3,304±938 | 1,684±412 |
| Specific methane yield (L $CH_4$/kg $VS_{added}$) | | 100±19 | 156±51 | 81±19 |
| Removal efficiency of COD (%) | | 56±13 | 51±16 | 43±20 |
| Removal efficiency of TS (%) | | 47±12 | 48±15 | 37±19 |
| Removal efficiency of VS (%) | | 52±12 | 51±15 | 42±17 |

*Notes: Data is shown as Mean ± Standard deviation; confidence level significantly was 95%.

Effluent VFA concentrations of the unmixed R1 (1,419±127 mg/L) was significantly higher ($p$ = 0.000) than those of R2 and R3. Also, the VFA/Alk ratio of R1 was found to be the highest among all studied reactors. High VFA level is the result of microbial interaction being failed to convert organic matters into suitable types of VFA for biogas production [20]. Accumulation of VFA have negative effects on the system as high VFA concentrations cause the inhibition of methanogenesis leading to the process failure [21]. That R2 and R3 could maintain effluent VFA concentrations in low levels (< 1,000 mg/L) suggested that mixing was crucial for the well-balanced microbial interactions of anaerobic digestion of dairy manure. In terms of COD and VS removal, comparable removal efficiencies were obtained from R1 and R2 while significantly lower efficiencies were detected from R3. This inferiority of R3 could partly be the results of excessive mixing and sludge wash out from the reactor.

Interestingly, both biogas production and specific methane yield obtained from R2 (3,304±938 L /d and 156±51 L CH4/kg VS) were significantly higher ($p$ = 0.000) those of R1 (2,084±356 L/d and 100±19 L $CH_4$/kg VS) and R3 (1,684±412 L/d and 81±19 L $CH_4$/kg VS). Moreover, R3 was found to produce the lowest biogas and provide the least specific methane yield, even when compared to those of the unmixed R1. These results indicated that for a particular type of anaerobic reactor, both the mixing intensity and position of mixing device were crucial and needed to be specifically determined. For the MCLs studied in this current work, installation of air-lift systems both in the front and rear parts (R3) which rendered the most complete mixing resulted in methane production efficiencies being the lowest. Deterioration of R3 efficiencies could be caused by the sludge wash out as effluent TS and VS of R3 were significantly higher than those of R1 and R2 ($p$ = 0.006 and 0.013, respectively). Results clearly showed that provision of the mixing system only in the front part (as in R2) was the most suitable arrangement for the treatment and biogas production from dairy waste. Under this installation, the reactor could reasonably remove VS, produce methane (which was accounted for 79.6% of the maximum specific methane yield gained from the BMP test) and provide the conditions suited for maintaining process stability.

## Conclusion

Both biogas flowrates and installation positions were found to significantly affect the mixing regimes and reactor performances. The suitable biogas flowrate was 20 L/min, which provided the best MCLs performance when installed only at the front part of the reactor. This work also suggested that the simple simulation program could be effectively used to assist in the determination of suitable mixing conditions for the anaerobic bioreactor.

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