Modelling of swine farm management for enhancement of biogas production and energy efficiency

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Abstract. A conventional all-in/all-out batch management, applied in most small to medium scale swine farming, often provides an inconsistent feed of wastewater for the biogas system, causing imbalance between the farm’s power requirement and its generation capacity. This study proposed two developed models that could be employed to ease this problem. In Model 1, the operation was divided into two batch intervals, while in Model 2, the operation used four separate batches. The developed models helped avoid an unnecessary long lag phase, allowing more stable anaerobic digestion performance, and a more evenly distributed amount of biogas being produced. Accordingly, the developed models more stably supplied energy for domestic use, achieving 36-44% reduction of the electricity expense, or a saving of 43,782 m³ biogas or 35,834 kWh equivalent compared with that of the conventional management. Moreover, excess biogas which occurred in the conventional management, up to 14,714 m³ or 12,043 kWh equivalent at the peak period, could be reduced by 79-100%, evaluated as a greenhouse gas reduction of 9,441 and 11,902 m³CO₂eq by Models 1 and 2, respectively. This suggests that without additional investment, more profit could be attained from the significant reduction of operating cost by proper farm management.

1. Introduction
Since the 1950s, agriculturists have learned to valorize wastewater from livestock farming by turning it into biogas via anaerobic digestion [1, 2]. This biogas comprises 60-65% methane (CH₄), 34-39% carbon dioxide (CO₂), and small amounts of hydrogen sulfide (H₂S), nitrogen (N₂), and steam [3]. Such great amount of methane in biogas enables farmers to generate their own electricity used in regular farming activities particularly for electronic equipment such as ventilation fans, feeders, and water pumps.

Currently, livestock farming is categorized into two modes, i.e. continuous and batch managements. Swine farms applying continuous management contain many large houses, each of which accommodates pigs sorted by age. This way, farmers can manage to have a desirable number of matured pigs to be sold continuously all year round. On top of that, with this scheme, it is certain that there is always sufficient flow of wastewater fed into biogas system thus enabling steady electricity production. However, such
management requires large space and is thus used only in large farms raising more than 5,000 heads [4]. Farms raising 50 to 5,000 heads, the scale of most swine farms in Thailand, on the other hand, normally apply batch management according to its ease in operation. With all-in/all-out scheme, this type of farming allows piglets at equal age to be loaded in houses. Altogether raised until fully grown, the whole batch are harvested. Prior to starting a new batch, farmers normally manage to stop operating for about two weeks for cleaning and rearrangement. During this period, no microbial nutrition is fed to the anaerobic digester, forcing microbes into starvation and death.[5] As the next batch begins, there inevitably occurs a lag phase where bacteria take approx. 2 weeks before starting to produce biogas again [6-9]. This leads to insufficient electricity for farming activities during such operation and thus extra electricity from Provincial Electricity Authority (PEA) is purchased. Moreover, at the end of the batch, a large quantity of wastewater with high oxygen demand (COD) is being discharging into the digester and this may hinder microbes from fully functioning and cause incomplete wastewater treatment.

To reduce lag phases and maintain stable biogas production, many research studies have been conducted. It was suggested that such lag phase could be eased by adjusting digestion temperature [10, 11], adding co-digestion material [12] and inoculum [13], and applying catalyst [14]. However, these techniques have not yet been practically applied for such purpose with regard to the high investment and complicated operation [15]. Mitigating such problems without additional cost, this study applied data collected from a conventional batch-managed swine farm in Thailand to develop two management models. The proposed models aim to pursue a continuous wastewater loading rate which would lead to a consistent production of biogas and electricity. Eventually, the potential of the proposed schemes was then evaluated in terms of economic and environmental aspects.

2. Methodology

2.1. Farm location and characteristics

A conventional batch management swine farm located in Wang Chan district, Rayong province, Thailand, is a model farm used in this study. It is representative of most medium-sized farms in Thailand. Raising 3,600 pigs, the farm uses four evaporation houses, each of which accommodates 900 heads. Typically, beginning at the equal age of 3 weeks old, piglets are loaded in the houses and are raised altogether for another 24 weeks, where they are fully grown and unloaded to be sold. Prior to beginning a new batch, farming is paused for two weeks for cleaning and maintenance.

2.2. Wastewater and biogas characteristics

While farming proceeds, a great amount of wastewater caused by swine excretion and daily house cleaning is generated. This wastewater is directed towards the treatment system, a 2,700 m$^3$ (4m*25m*27m), covered lagoon, in which biogas is produced via anaerobic digestion. Fed into a 55-kW generator, the produced biogas allows farmers to generate their own electricity to be used in regular farming activities. Weekly, 250 ml of wastewaters at the inlet and outlet of the lagoon were sampled with amber bottles and stored at 4°C until analysis. Characterizing wastewater, the collected samples were analyzed for total solid (TS) and volatile solid (VS) according to the APHA 2005 method [16], COD using a multiparameter bench photometer, HI 83099 (Hanna instruments, Romania) and pH. Wastewater volume fed into the lagoon was recorded on a daily basis. The produced biogas was also collected weekly, and its composition was examined using a biogas analyzer, Biogas 5000 (Geotech, England). Moreover, to study the electricity demand of the conventional farming, the monthly data of electricity expense before the installation of the biogas production system was collected.
2.3. Calculation of biogas production

The daily amount of biogas obtained from the system was calculated from COD content and wastewater flow rate, following Equations 1-3 [9].

Step 1: Determination of COD converted to methane

\[ COD_{CM} = COD_{inf} - COD_{eff} + COD_{vss} \]  
(1)

where

\( COD_{CM} = \text{Influent COD converted to methane} \ (g \cdot L^{-1}) \)

\( COD_{inf} = \text{Influent COD from experiment} \ (g \cdot L^{-1}) \)

\( COD_{eff} = \text{Effluent COD from experiment} \ (g \cdot L^{-1}) \)

\( COD_{vss} = \text{COD concentration of volatile suspended solid} \ (g \cdot L^{-1}) \)

Step 2: Determination of methane production rate

\[ \text{Methane}_{produced} = \text{Methane production at } 35^\circ C \times COD_{loading} \]  
(2)

where

\( COD_{loading} = \text{Amount of wastewater} \ (L) \times COD_{CM} \)

\( \text{Methane}_{produced} = \text{Amount of methane} \ (L) \)

\[ \text{Methane production at } 35^\circ C = \frac{25.29 \text{ L} \cdot \text{mole}^{-1}}{64 \text{ g} \cdot \text{mole}_{CH_4}} \]

\[ = 0.4 \text{ L}_{CH_4} \cdot \text{g}^{-1} \cdot \text{COD}_{converted} \]

Step 3: Determination of energy produced

\[ \text{Energy produced} = \text{Methane}_{produced} \times E \]  
(3)

where

\( E = \text{LHV of methane} \)

Assumptions:

\( \text{LHV of methane} = 50 \text{ MJ} \cdot \text{Kg}^{-1} \)

\( \text{Thermal efficiency} = 30\% \)

\( \text{Turbine efficiency} = 60\% \)

2.4. Development of farm management models

For the consistency of biogas production, it is necessary to have wastewater fed into the lagoon continuously. Taking into consideration this matter, two management models were developed as shown in Figure 1. Model 1, instead of having all 4 houses operated with the same interval, the operation was rearranged such that Houses 1 and 2 were operated at the same interval which was three months separated from Houses 3 and 4. While in Model 2, the operation was with four houses as four different batches each with 1.5 months interval. Like the conventional management, the two developed models were also stopped for cleaning and maintenance prior to proceeding into the next cycle.
Evaluating the performance of the developed models, costs and benefits in terms of environmental and economic aspects were considered through the correlation between biogas production, purchased electricity, and excess biogas. In case the produced biogas was insufficient to meet the energy demand, extra electricity was purchased from the Provincial Electricity Authority (PEA), at the rate of 10 cents/kWh [17]. When the amount of biogas produced by the farm was higher than the energy demand, there occurred excess energy. In such cases two routes were considered. In case the farm managed to connect the biogas electricity to the government grid, the surplus power could be sold at the price of 8 cents/kWh (data from Electricity Generating Authority of Thailand, EGAT). Otherwise, it would be burned off into the atmosphere, causing air pollution. In this case, the amount of excess biogas was considered in terms of Global Warming Potential (GWP) values relative to CO$_2$, which is 21 times for methane [18].

3. Results and Discussion

3.1. Conventional management with biogas production

The majority of electricity consumption in the farm is dedicated to the ventilation fans, feeder equipment, and water pumps. In the case where there is sufficient organic matter in the wastewater lagoon, the farm is able to manage and only uses electricity generated from biogas. Only when biogas is inadequate, the farm needs to switch to PEA electricity. Figure 2 shows a comparison between biogas produced by the current farm management and the power needed for farm activities. Table 1 indicates that both biogas yield and power consumption were dependent on swine age and the amount of wastewater produced. Starting from the equal age of 3 weeks old, all the piglets were raised in the evaporation houses until they reached the slaughter weight at Week 24. This management resulted in a continuous increase in energy consumption, from 0.17 to 2.14 kWh/swine-week for Week 1 to 24. After the harvest (at Week 24), farming was paused for 2 weeks for cleaning and re-arrangement and thus energy consumption during the break, Weeks 25-26, was relatively small and could be negligible. During this break interval, there was no organic matter supplied to the biogas pond, and this finally

![Figure 1. Farm management models (black bands represent the cleaning weeks and gray bands denote the operation period)](image_url)
ceased the microbial activity. Although the next batch started straight after the break, there was still a lag phase (Weeks 32-40) where no biogas was generated and it was usually not until Week 45 that the biogas generation rate was back at its maximum rate. This is not uncommon as it generally takes 4-10 weeks for anaerobic fermentation to begin producing biogas again after a break [9].

To ensure uninterrupted production of biogas, it is necessary to maintain the organic loading rate, i.e. maintaining the level of COD loading in the wastewater fed to the digester. With the current management, as no wastewater was fed to the digester for 2 weeks during the absence of wastewater, some microorganisms in the system was starved and become inactive, resulting in no biogas yield from Week 5 to 10. Therefore, as shown in Figure 2, a lag-phase where the production of biogas proceeds slowly was observed every time a new cycle was started. Thus, all the electricity used during this stage needed to be purchased from PEA. On Week 11-15, as the piglets were still very small, the amount of feces excreted was minimal, causing low COD wastewater in the lagoon and thus resulting in a lag-phase of biogas production. Even though the production of biogas began to proceed faster from Week 15-25, it was not yet fast enough to meet the demand and thus some amount of power from PEA was still needed. From Week 20 onward, when swine was fully grown, wastewater with a high COD of 8,000-9,900 mg/l was continuously loaded to the lagoon with the flow rate of 500,000 m$^3$/week. Consequently, the maximum biogas yield was achieved and thus the farm could manage to totally use electricity from biogas.

However, despite the highest production of biogas during Week 25-32, farming activities were paused during this period and only a very small amount of electricity was needed at the beginning of the next cycle. This resulted in a surplus amount of biogas, which inevitably had to be burned off into the atmosphere, causing environmental pollution[19].

![Figure 2. Correlation of energy consumption, amount of biogas, and volume of wastewater produced from conventional management](image-url)
Table 1. Weekly rate of wastewater, biogas production and energy consumption per swine head

| Age (week) | Weekly rate per swine head | Weekly rate per swine head | Energy consumption per swine head |
|------------|---------------------------|---------------------------|----------------------------------|
|            | Wastewater (L/week)       | Biogas production (kWh/week) |                     |
| 1-4        | 27                        | 0.04                      | 0.17                            |
| 5-8        | 74                        | 0.16                      | 0.23                            |
| 9-12       | 96                        | 0.23                      | 0.30                            |
| 13-16      | 112                       | 0.24                      | 0.39                            |
| 17-20      | 137                       | 0.38                      | 0.51                            |
| 21-24      | 221                       | 0.42                      | 2.14                            |

3.2. Scenario analysis (Models 1 and 2) and biogas production

The results of the farm management modelling are shown in Figure 3 which indicates significant changes for biogas production and energy consumption. Obviously, the period with zero biogas production could be removed by both models. Moreover, the lag-phase and fluctuation of biogas production were reduced. Since energy consumption was dependent on swine age, when the conventional management was modified to Models 1 and 2 in which swine ages were more evenly distributed, there occurred changes in trends of energy consumption. This was because the two models allowed continuous feeding of wastewater into the lagoon and thus prevented microbial death caused by starvation during transition to the next batch, as occurred in the conventional management. It can be seen from Figure 3A that with Model 1, 400-2,150 m³ of biogas which was equivalent to 320-1,760 kWh could be produced weekly. Compared to the conventional management, Model 1 could manage to reduce the wasted surplus biogas by 80%. However, there was still a period (Week 2-5 and Week 15-17) where biogas production exceeded weekly demand of the farming activity by 800 m³. Model 2, as shown in Figure 3B, produced a lower weekly amount of biogas (470-1,200 m³), however its consistency with average weekly biogas production of 843 m³ (690 kWh equivalent) was provided parallel to the demand of farming activities. Therefore, the wasted surplus biogas was not observed in Model 2.

Figure 3. Comparison of biogas yield and energy consumption obtained from (A) Model 1 and (B) Model 2
3.3. Economic and environmental analysis
To evaluate the performance of each model, costs and benefits in terms of environmental and economic aspects were considered through the correlation between biogas production, purchased electricity, and excess biogas. The results show that, annually, the amount of biogas obtained from each model was rather similar, in the range of 36,840-40,958 m$^3$ (30,152-33,103 kWh equivalent). Due to the shortened lag phase as a result of continuous feed of wastewater, the annual amount of biogas produced by Models 1 and 2 were higher than that obtained from conventional management of up to 9 and 11 %, respectively. On average, the energy needed to complete annual farming activity was 65,320 m$^3$ (53,462 kWh equivalent) as shown in Figure 4. However, there was deviation depending on swine growth. In some periods, the farm managed to produce less biogas than it needed and thus extra power from PEA was included, as shown in Table 2. Particularly, despite the similar average amounts of biogas produced per year for all managements, Models 1 and 2 could reduce the expense caused by imbalanced power consumption of up to 36% and 44%, equivalent to 999 and 1,228 USD/year, respectively. While there was a period where the amount of biogas was insufficient, there occurred also a period where biogas was excess to the demand, which, in this study, was divided into 2 routes for economic evaluation. In case that the farm managed to connect biogas electricity to the government grid, the surplus power could be sold at the price of 8 cents/kWh. Accordingly, by conventional management and Model 1, the farmer would earn 933 and 193 USD/year from selling this excess biogas power, respectively. Considering the saving cost from purchasing electricity and the earnings from selling excess biogas electricity, Model 1 and 2 could save the expenses by 14 and 16 %, which accounted for 258 and 295 USD/year, respectively. However, in another case where the surplus biogas was not sold according to the national policy, it would be burned off into atmosphere and resulted in air pollution. By conventional management, the farm would annually burn over 14,714 m$^3$ (12,043 kWh) into the atmosphere. Considering this in terms of CO$_2$ equivalent, such emission was calculated as 19,127 m$^3$ CO$_2$ equivalent emitted per year to the atmosphere. By the proposed managements (Model 1 and 2 respectively), as the excess biogas could be reduced to 3,043 m$^3$/year and zero (79-100% reduction), a Greenhouse Gas (GHG) reduction of 9,440 and 11,902 m$^3$ CO$_2$ equivalent/year (from the electricity supplement) could be achieved. Based on the results obtained from this study, Model 2 was most effective as it could most reduce GHG emission with regard to a great decrease in excess biogas. On top of that, Model 2 could best lower the farming expense caused by electricity purchase.

![Figure 4](image.png)

**Figure 4.** Comparison of biogas yield, purchased electricity, and excess biogas obtained from the conventional management, Model 1 and 2
Table 2. Evaluation of cost savings by Model 1 and 2

|                                | Conventional model | Model 1 | Model 2 |
|--------------------------------|--------------------|---------|---------|
| Cost of electricity purchased from PEA (USD/year) | 2,776              | 1,777   | 1,548   |
| Economic value of excess biogas (USD/year)         | 933                | 193     | 0       |
| Cost saving (excess biogas unsellable) (%)         | -                  | 36      | 44      |
| Cost saving (excess biogas sellable) (%)           | -                  | 14      | 16      |

4. Conclusions
The current conventional batch management results in imbalance between the produced biogas and the farm’s energy consumption. In other words, the amount of biogas produced during high energy demand was deficient causing undesired extra electricity expense. On the other hand, at some point, biogas was produced at high rate against low demand, resulting in a significant amount of wasted biogas. With the two models developed in this study, a more consistent flow of wastewater was achieved, and thus the problems found in the conventional management were eased by the resulting stable biogas and electricity production. Owing to the change in energy demand obtained from each model, the purchased electricity could be reduced by 36 and 44% and the excess biogas was reduced by 79 and 100%, by Models 1 and 2, respectively. Applying the developed models from this study to other conventional swine farms would contribute to a great reduction of GHG emission and electricity expense.

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