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ORIGINAL PAPER

Economic Analysis of Swine Farm Management for the Enhancement of Biogas Production and Energy Efficiency

N. Putmai[1] · T. Jarunglumlert[2] · C. Prommuak[3] · P. Pavasant[4] · A. E. Flood[1]

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Abstract
The conventional all-in/all-out batch management that is applied in most small to medium swine farms often provides an inconsistent feed of wastewater to biogas systems, causing an imbalance between the power requirements and generation capacity of a farm. This study proposes two alternative models that can be employed to ease this problem. In Model 1, the operation was divided into two offset batch intervals, while in Model 2, the operation used four separate offset batch intervals. The models developed here help avoid an unnecessary long lag phase in the digester, allowing more stable anaerobic digestion performance and more evenly distributed biogas production. Accordingly, the models produce a more stable supply of energy for domestic use, achieving a 36–44% reduction in the electricity expense or a savings of 43,782 m^3 biogas/year or 35,834 kWh equivalent compared with that of conventional management. Conventional farm management has periods of excess and deficient biogas production; excess biogas is produced at a rate of up to 14,714 m^3/year or 12,043 kWh equivalent at the peak period. This excess could be reduced by 79–100% by using the proposed farming models. This reduction is equivalent to greenhouse gas reductions of 9441 and 11,902 m^3 CO_2 eq./year by Models 1 and 2, respectively. Finally, a sensitivity analysis is used to show how the profitability of biogas plants would vary due to changes in some key parameters, such as the electricity buyback price. The results suggest that more profit could be attained from a significant reduction in operating costs by proper farm management without requiring additional investment.

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✉ A. E. Flood
Adrian.flood@vistec.ac.th

1 School of Energy Science and Engineering, Vidyasirimedhi Institute of Science and Technology, Rayong, Thailand

2 Faculty of Science, Energy and Environment, King Mongkut's University of Technology North Bangkok (Rayong Campus), Rayong, Thailand

3 Energy Research Institute, Chulalongkorn University, Bangkok, Thailand

4 Tree Moments Co., Ltd, Bangkok, Thailand

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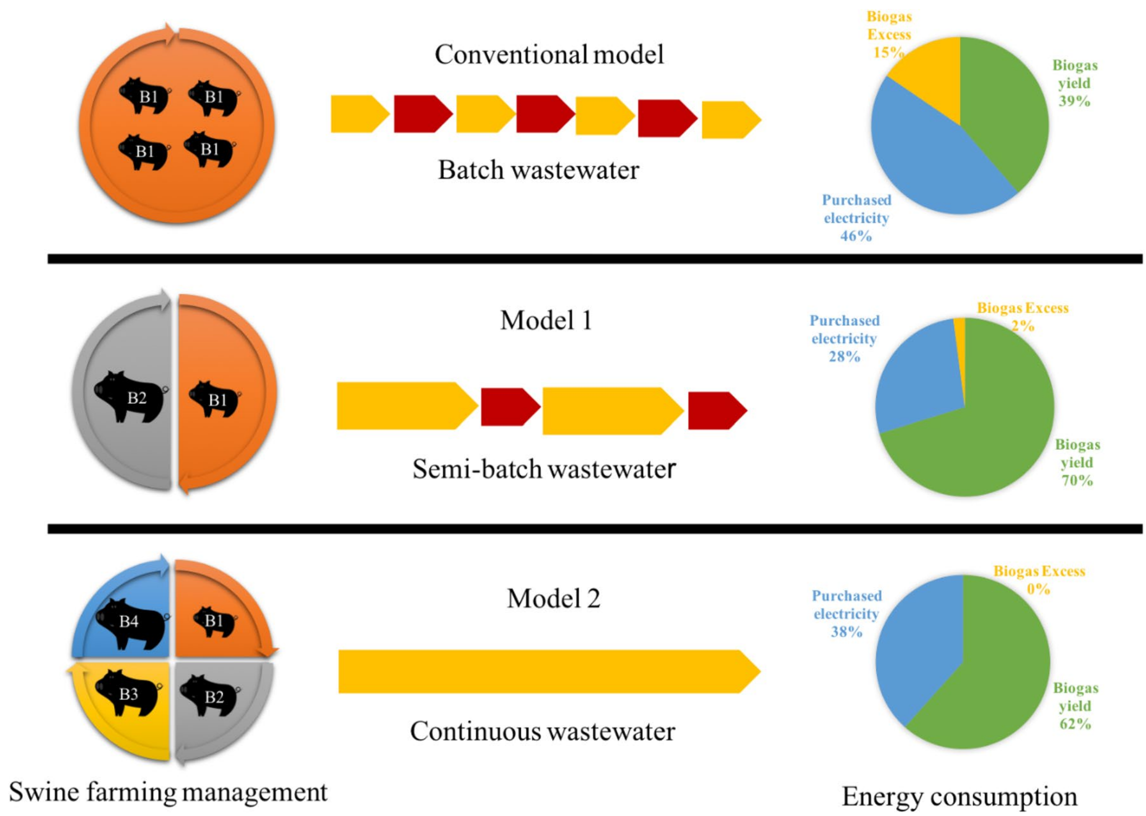
Graphic Abstract



Keywords Swine farming · Wastewater · Biogas · Renewable energy

Statement of Novelty

Small- to medium-scale swine farms are economically important in many developing countries. This study develops improved farm management models to enhance the efficiency of biogas production and improve the economics of operation of these farms. The currently used model raises swine in single batches and is inefficient for continuous production of wastewater to efficiently produce biogas for renewable energy production since microorganisms die during periods when no wastewater is fed. Raising swine in a series of partially overlapping offset batches gives a more continuous flow of wastewater which improves the operation of biogas production and allows for improvements in the economics of the farm. The new models also reduce periods of excess biogas production which reduces the environmental consequences of the farm

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 (CH_4), 34–39% carbon dioxide (CO_2), and small amounts of hydrogen sulfide (H_2S), nitrogen (N_2), and water vapor [3]. The significant amount of methane in biogas enables farmers to generate their own electricity, which is 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 management. Swine farms that apply continuous management contain many large houses, each of which accommodates pigs sorted by age. When continuous management is used, farmers have a suitable number of mature pigs to be sold continuously throughout the year. In addition, with this scheme, it is certain that there is always a sufficient flow of wastewater fed into the biogas system, thus enabling steady electricity production. However, such management requires large space and is thus used only in large farms raising more than 5000 livestock [4]. Farms raising 50 to 5000 livestock, the scale of most swine farms in Thailand, normally apply batch management due to its ease of operation. With an all-in/all-out scheme, this type of farming allows piglets of equal age to be loaded in houses. The swine are raised together until fully grown, and then the whole batch is harvested. Farmers normally stop operating for approximately 2 weeks prior to starting a new batch to clean and maintain the housing. During this period, no microbial nutrition is fed to the anaerobic digester, forcing microbes into starvation and death [5]. As the next batch begins, a lag phase inevitably occurs where bacteria take approximately 2 weeks before starting to produce biogas again [6–9]. This phase leads to insufficient electricity for farming activities during the lag phase, and thus extra electricity is purchased from the Provincial Electricity Authority (PEA). Moreover, at the end of the batch, a large quantity of wastewater with high chemical oxygen demand (COD) is discharged into the digester, which may hinder microbes from fully functioning and cause incomplete wastewater treatment.

Many studies have been conducted to reduce lag phases and maintain stable biogas production [10]. It has been suggested that the problems with the lag phase could be eased by adjusting the digestion temperature [11, 12], adding co-digestion material [13] and inoculum [14], applying a catalyst [15], and utilizing multiple stages and high-pressure anaerobic digestion [16–18]. However, these techniques have not yet been applied practically since they tend to have high investment cost and/or complicated operation [2, 19]. Hoping to mitigate such problems without incurring 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 that 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.

Methodology

Farm Location and Characteristics

A conventional batch management swine farm located in Wang Chan district, Rayong Province, Thailand, is the model farm used in this study. This farm is representative of most medium-sized farms in Thailand. Raising 3600 pigs, the farm uses four evaporation houses, each of which accommodates 900 livestock. Typically, piglets are loaded in the houses at the age of 3 weeks and are raised together for another 24 weeks, when they are fully grown and unloaded to be sold. Prior to beginning a new batch, farming is paused for 2 weeks for cleaning and maintenance.

Wastewater and Biogas Characteristics

While farming occurs, a great amount of wastewater caused by swine excretion and daily house cleaning is generated. This wastewater is directed towards the treatment system, a 2700 m^3 (4 m×25 m×27 m) covered lagoon, in which biogas is produced via anaerobic digestion. The produced biogas is fed into a 55-kW generator, which allows farmers to generate their own electricity to be used in regular farming activities. Weekly, 250 mL wastewater samples were collected at the inlet and outlet of the lagoon with amber bottles and stored at 4 °C until analysis. For characterization of the wastewater, the collected samples were analyzed for total solids (%TS) and volatile solids (%VS) according to the APHA 2005 method [20], COD using a multiparameter bench photometer, HI 83,099 (Hanna instruments, Romania) and pH. The volume of wastewater fed into the lagoon was recorded daily. The produced biogas was also collected weekly, and its composition was examined using a biogas analyzer, Biogas 5000 (Geotech, England). The composition of the biogas was consistent over the production period of 25 weeks and was typically approximately 60% methane and 40% CO_2. Trace amounts of H_2S, CO and H_2 were also detected; however, these were in the ppm range. The data for the compositions of the biogas are shown in the supplementary information. Moreover, to study the electricity demand of conventional farming, monthly electricity expense data before the installation of the biogas production system were collected.

Calculation of Biogas Production

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

Step 1 Determination of the ideal conversion of COD to methane

$$COD_{CM,Th} = COD_{Inf} - COD_{Eff} + COD_{VSS} \tag{1}$$

where $COD_{CM,Th}$ = Theoretical COD conversion to methane (g L^{-1}), COD_{Inf} = COD in the influent (g L^{-1}), COD_{Eff} = COD in the effluent (g L^{-1}), COD_{VSS} = COD due to volatile suspended solids (g L^{-1}).

Step 2 Determination of methane production rate

$$F_{Meth,Th} = X_{Meth,Th} \cdot COD_{Loading}$$

where $F_{Meth,Th}$ is the theoretical production of methane (L day^{-1}), $X_{Meth,Th}$ is the theoretical conversion of COD to methane, and $COD_{Loading}$ is the COD loading (g day^{-1}).

$$COD_{Loading} = F_W \cdot COD_{CM,Th}$$

where F_W is the wastewater flow (L day^{-1}). The theoretical conversion of COD to methane at 35 °C is calculated from the maximum potential conversion of COD to methane and the molar volume of methane as an ideal gas at 35 °C.

$$X_{Meth,Th} = \frac{25.29\left(L \cdot mole^{-1}\right)}{64\left(gCOD \cdot mole_{CH_4}^{-1}\right)} = 0.4\left(L_{CH_4} \cdot g_{CODConverted}^{-1}\right) \tag{2}$$

Step 3 Actual amount of methane producedThe actual amount of methane produced is smaller than the ideal amount due to side products, particularly CO_2. It was previously found that methane conversion was only 53% of the ideal value [21], and this is also a conservative estimate of the biogas measured in this study (see the supplementary information) and thus

$$F_{Meth,Act} = 0.53F_{Meth,Th}$$

Step 4 Determination of the energy produced

$$E_{Prod} = F_{Meth,Act} \cdot LHV_{CH_4} \tag{3}$$

where LHV represents the lower heating value of methane. In calculating the energy production, we also assume typical thermal and turbine efficiencies for the generator: the values of the required parameters are LHV of methane = 50 MJ kg^{-1}, Thermal efficiency = 30%, Turbine efficiency = 60%

Development of Farm Management Models

It is necessary to feed wastewater into the lagoon continuously for consistent biogas production. Taking this into consideration, two farm management models were developed, as shown in Fig. 1. In Model 1, instead of all 4 houses operating with the same interval, the operation was arranged so that Houses 1 and 2 were operated using the same interval, and Houses 3 and 4 were operated on an interval that began 3 months after Houses 1 and 2. In Model 2, the operation used the four houses in four different batches offset by 1.5 month intervals. Similar to conventional management, the two new models also had periods where the operation was stopped for cleaning and maintenance prior to proceeding to the next cycle.

Economic and Environmental Evaluation of the 3 Models

Economic aspects were considered through the correlation between biogas production, purchased electricity, and excess

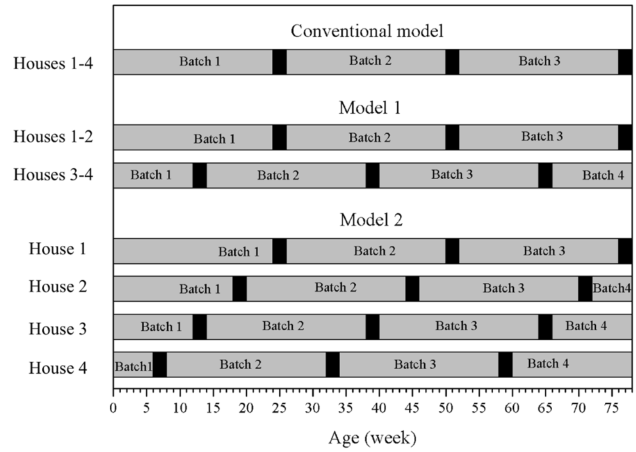


Fig. 1 Farm management models (gray bands denote the operation periods and black bands represent the cleaning periods)

biogas [22]. If the produced biogas was insufficient to meet the energy demands of the farm, extra electricity was purchased from the PEA at a rate of 10 cents/kWh [23]. When the amount of biogas produced by the farm was higher than the energy demand, excess energy occurred. In such cases, two routes were considered. In cases where the farm could connect the electricity produced from the biogas to the government grid, the surplus power could be sold at a price of 8 cents/kWh (data from Electricity Generating Authority of Thailand, EGAT). Otherwise, the excess biogas is burned off into the atmosphere, causing greenhouse gas emissions. In this case, the amount of excess biogas was considered in terms of the global warming potential (GWP) value relative to CO_2, which is 21 times that of methane [24].

Calculation of Economic Parameters

The economic analysis started with the collection of the investment cost and operational cost, which is necessary to manage biogas production. Then, economic parameters such as the net present value (NPV), internal rate of return (IRR), profitability index (PI), payback period (PP), and level cost of electricity (LCOE) were calculated according to Eqs. 4–8 [22, 25].

Net Present Value (NPV)

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{4}$$

where B_t = income per year for year t, C_t = Expenses per year for year t, r = Real interest rate, t Year (1,2,3,4, …)

Internal Rate of Return (IRR)

$$0 = \sum_{t=0}^{n} \frac{B_t - C_t}{(1 + IRR)^t} \tag{5}$$

Profitability Index (PI)

$$PI = \frac{\sum PV \text{ of proceeds}}{PV \text{ of initial investment}} \tag{6}$$

where $PV =$ income in each year

$$PP = \textit{Last year with positive cash accumulation} + \frac{\textit{Last positive cash accumulation value}}{\textit{Proceeds in first year that cash accumulation is negative}} \tag{7}$$

Levelized Cost of Electricity (LCOE)

$$LCOE = \frac{\sum_{t=0}^{n} \frac{C_t - M_t}{\left(1+\frac{r}{100}\right)^t}}{\sum_{t=0}^{n} \frac{E_t}{\left(1+\frac{r}{100}\right)^t}} \tag{8}$$

where C_t = Capital cost in year t (USD). M_t = operating and maintenance cost in year t (USD/year), E_t = electricity required for year t (kWh/year), r = discount rate

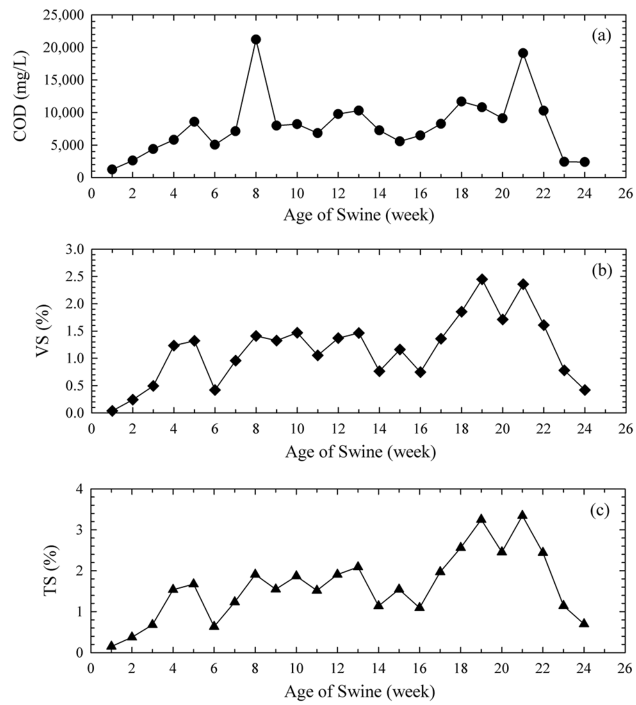


Fig. 2 Evolution of **a** COD, **b** VS, **c** TS in the conventional management model

Results and Discussion

Conventional Management with Biogas Production

The majority of electricity consumption in the farm is dedicated to ventilation fans, feeder equipment, and water pumps. When there is sufficient matter in the wastewater lagoon, the farm is able to produce enough biogas to use only electricity generated from biogas. When the amount of biogas is inadequate, the farm needs to switch to electricity purchased from PEA.

The COD has a very strong effect on the ultimate biogas yield, as well as the methane content. In the mesophilic temperature range of 25 to 35 °C, the biogas production rate is necessarily dependent on the VS content of the feed, as methane comes from degradation of VS. The values of VS, TS, and COD determine the quality of the wastewater and have a direct bearing on the production of the biogas, as shown in Fig. 2a–c. The biogas yield is dependent on the age of the swine being raised, with periods where older swine are housed having better wastewater properties and therefore better biogas yield. There are peaks in the COD at weeks 8 and 21; however, these peaks are due to the normal stochasticity in the operation. This work was conducted in an actual small-size swine farm, where most operations are performed manually. Therefore, there are periods at which some of the activities, such as farm washing and feces collection, were not reproducibly carried out, and this inevitably caused some fluctuation in the performance of the operations. However, these points that temporarily deviated from the norm did not seriously affect the performance of the farm in the long run as the operation went back to normal as soon as the farm management was returned to the normal schedule.

The loading rate is defined as the flow rate of wastewater fed to the continuous digester. If the loading rate is higher than the optimum, the system may become acidified and thus inhibit digestion and reduce the production of biogas. TS is also an important attribute of digester operation since the ability to treat high-TS wastewaters leads to smaller digesters. It has been found that improved biogas yields could be achieved in high-TS digesters compared to low-TS digesters operating with the same retention time [26].

Figure 3 shows a comparison between the 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, COD loading and the amount of wastewater produced. In the conventional management model, swine are loaded simultaneously at 3 weeks old, and all swine are raised in evaporation houses until they reach slaughter weight at week 24. This management method resulted in a continuous increase in energy consumption, from 0.17 to 2.14 kWh/swine·week for weeks 1 to 24. After the harvest (at week 24), farming

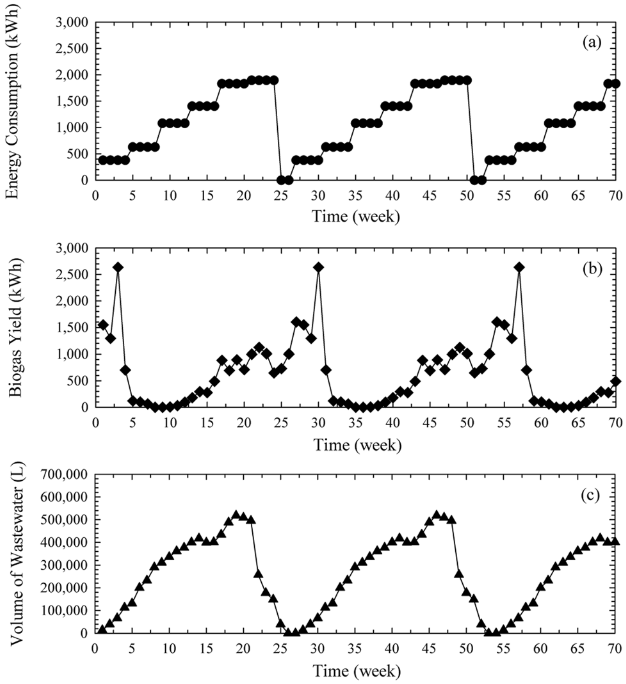


Fig. 3 Evolution of **a** energy consumption, **b** biogas yield, **c** volume of wastewater produced from the conventional management model

Table 1 Weekly rate of wastewater, biogas production and energy consumption per swine

Age (week)	Weekly rate per swine			
	Waste-water (L/week)	COD loading (kg/week)	Biogas production (kWh/week)	Energy consumption (kWh/week)
1–4	27	0.13	0.04	0.17
5–8	74	0.60	0.16	0.23
9–12	96	0.79	0.23	0.30
13–16	112	0.83	0.24	0.39
17–20	137	1.37	0.38	0.51
21–24	221	2.12	0.42	2.14

was paused for 2 weeks for cleaning and maintenance, and thus, energy consumption during this period, weeks 25–26, was relatively limited and could be neglected. During the period when no swine were raised, there was no organic matter supplied to the biogas pond, which caused the microbial activity to cease. Although the next batch started immediately 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 returned to its maximum rate. This situation 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. If the conventional management model was used, there was no wastewater fed to the digester for 2 weeks during the cleaning period; some microorganisms in the digester were starved and became inactive, resulting in zero biogas yield from week 5 to week 10. Therefore, a lag phase where the production of biogas proceeds slowly was observed every time a new cycle was started, as shown in Fig. 3. Thus, all the electricity used during this stage needed to be purchased from PEA. During the period of weeks 11–15, when the piglets were still very small, the amount of feces excreted was minimal, resulting in low COD wastewater in the lagoon and thus a lag phase of biogas production, as shown in Fig. 2a. Even though the production of biogas began to proceed faster in the period from weeks 15–25, it was not yet fast enough to meet the demand, and thus, some amount of power from the PEA was still needed. From week 20 onward, when the swine were fully grown, as shown in Fig. 2a, wastewater with a high COD of 8000–9900 mg/L was continuously loaded to the lagoon with a flow rate of 500,000 m^3/week. Consequently, the maximum biogas yield was achieved at this time, and the farm could manage to use only electricity from biogas.

However, despite the highest production of biogas during weeks 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 situation resulted in a surplus amount of biogas, which inevitably had to be burned off into the atmosphere since the farm was not connected to the national grid, causing environmental pollution [27].

Scenario analysis (Models 1 and 2) and Biogas Production

The results of the farm management modeling for Models 1 and 2 are shown in Figs. 3, 4, and 5, which indicate significant changes in biogas production and energy consumption. 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, changes in trends of energy consumption occurred. These changes occurred 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. Figure 5b shows that with Model 1, 400–2150 m^3 of biogas, which was equivalent to 320–1760 kWh, could be produced

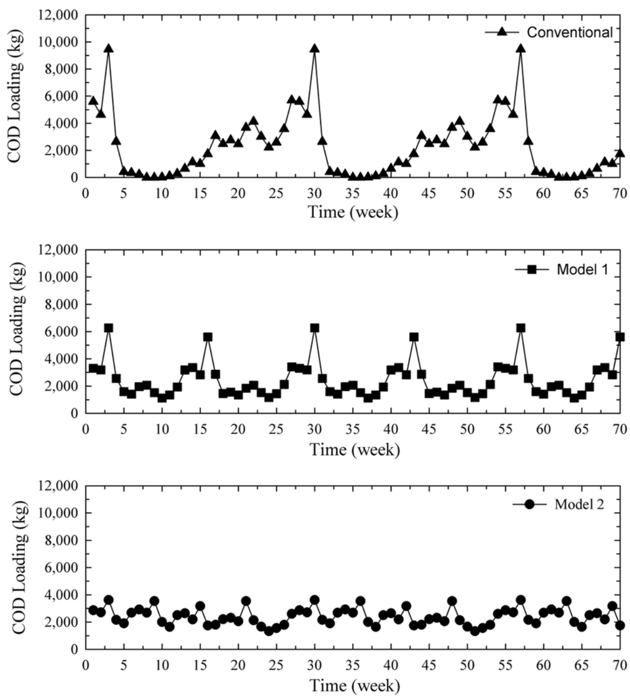


Fig. 4 Changes in COD in wastewater during the anaerobic digestion process at swine farms

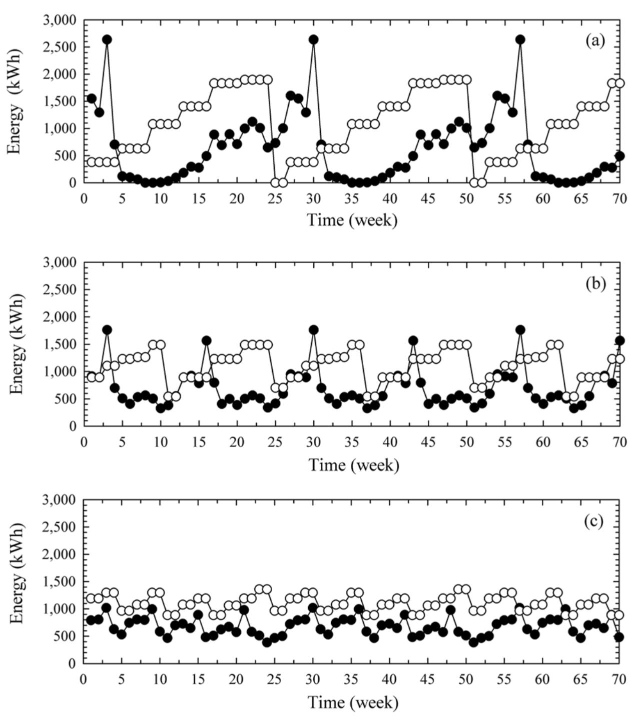


Fig. 5 Comparison of biogas yield (black circle) and energy consumption (white circle) obtained from **a** conventional model, **b** Model 1, **c** Model 2

weekly. Model 1 could reduce the wasted surplus biogas by 80% compared to the conventional management model. However, there were still periods (weeks 2–5 and 15–17) where biogas production exceeded the weekly demand of farming activity by 800 m^3. Model 2, as shown in Fig. 5c, produced a lower weekly amount of biogas (470–1200 m^3); however, it exhibited higher consistency of biogas production, with an average weekly biogas production of 843 m^3 (690 kWh equivalent) provided parallel to the demand of farming activities. Therefore, wasted surplus biogas was not observed in Model 2.

Economic Analysis

Energy Cost Saving

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 the total annual amount of biogas obtained from each model was rather similar, in the range of 36,840–40,958 m^3/year (30,152–33,103 kWh equivalent). However, due to the shortened lag phase, the annual amount of biogas produced by Models 1 and 2 was slightly higher than that obtained from conventional management by up to 9 and 11%, respectively. On average, the energy needed to achieve the annual farming activity was 65,320 m^3/year (53,462 kWh equivalent), as shown in Fig. 6. 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 1228 USD/year, respectively. While there was a period where the amount of biogas was insufficient, a period where biogas was more than the demand also occurred, which, in this study, was divided into 2 routes for economic evaluation. When the farm managed to connect generated biogas electricity to the government grid, the surplus power could be sold at a price of 8 cents/kWh. Accordingly, when the conventional management model was compared to Model 1, the farmer would earn 933 and 193 USD/year from selling this excess biogas power, respectively. Considering the costs saved from reduced electricity purchase and the earnings from selling excess biogas-produced electricity, Models 1 and 2 could reduce expenses by 14 and 16%, which are equivalent to 258 and 295 USD/year, respectively.

The Economic Potential Assessment Results of Electricity from Wastewater in Swine Farms

The purpose of this study is to determine the cost of generating electricity from wastewater plants associated with swine farms through the model in the following table. To determine the cost of producing electricity from the effluent from farmed pigs, each model was considered using the assumptions shown in Table 3. The details of equipment costs and building, land and management costs are shown in Table 4.

This analysis can assess the economic value of each model in terms of electricity generation. As shown in Table 5, Models 1 and 2 have an improved economic value compared to the conventional model if electricity cannot be sold back to the government. The IRR is larger than the real interest rate, which shows that it is worthwhile to invest in

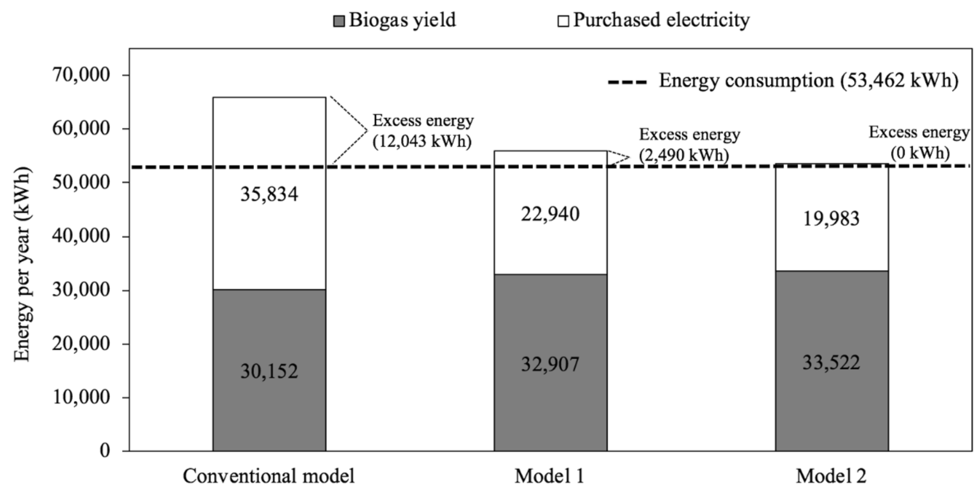


Fig. 6 Comparison of biogas yield, purchased electricity, and excess biogas obtained from conventional management and Models 1 and 2

Table 2 Evaluation of cost savings by Models 1 and 2

	Conventional model	Model 1	Model 2
Cost of electricity purchased from PEA (USD/year)	2776	1777	1548
Economic value of excess biogas (USD/year)	933	193	0
Cost saving (excess biogas: cannot sell to the grid) (%)	–	36	44
Cost saving (excess biogas: can sell to grid) (%)	–	14	16

Table 3 Key assumptions for the development of the model

Key assumptions	Category	Quantity	Unit
Investment cost	Time	20	Years
	Real interest rate	6.275	%
	Equipment	12,063	USD
	Building, land, and working capital	10,587	USD
Operating and maintenance cost	Raw material	0	USD
	Labor (operating and maintenance)	635	USD/year
	Annual maintenance cost (started 0.76% and *3% every year)	0.76	%
	Changing spare parts	1.83	% Of equipment cost/8 years
	Depreciation allowance	(Equipment cost-asset write-off)/time	USD/year
	Asset write-off	4	% Of equipment cost
Energy prices	Electricity purchasing price	10.79	Cents/kWh
	Electricity buyback price	0–20.00	Cents/kWh

Table 4 Details of the investment costs that are shown in Table 3

List of details	Cost (Thai Baht)	Cost (USD)
Details of equipment		
Electric generator	350,000	11,111
Biogas H_2S scrubber system	30,000	952
Sum of the equipment prices	380,000	12,063
Details of building, land and working capital		
Preparation of biogas pond (~ 540 m^2)	50,000	1587
Biogas system and plastic covers	220,000	6984
Setting up the biogas system	13,500	429
Piping for wastewater and biogas	30,000	952
Building for electric generator	20,000	635
Sum of the building, land and working capital	333,500	10,587

Table 5 Comparison of the economic measures of each model

Model	Internal rate of return (IRR, %)	Profitability index (PI)	Payback period (PP, year)	LCOE (cents/kWh)	NPV
Conventional model	9.10	1.24	9.09	9.11	5370
Model 1	10.74	1.39	8.13	8.35	8721
Model 2	10.86	1.40	8.06	8.29	8960

this process, and Model 2 has the highest IRR. This result shows that it is worthwhile to invest in farming with this model, with much the same conclusion from the NPV and PI calculations.

The PP is the point where you can have a return of the capital. This point occurs over a very short period of time, particularly for Model 2. Considering the LCOE, the production cost of the conventional model is the highest. Considering that the LCOE of the conventional farming model has the highest cost of production, we can see that Models 1 and 2 can improve the economic potential of the farming activities.

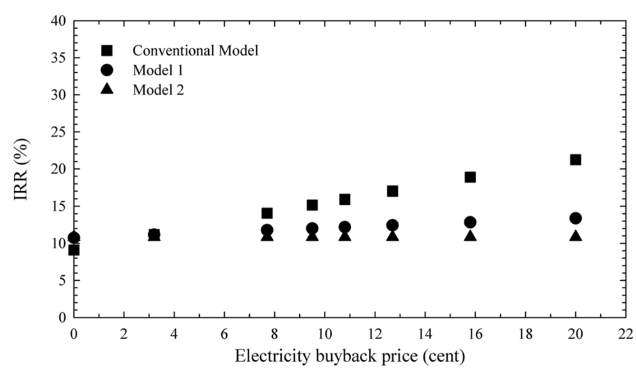


Fig. 7 Sensitivity of IRR with respect to electricity buyback price

Sensitivity Analysis

Here, we analyze the sensitivity of the profitability analysis of each model, as shown in Figs. 7 and 8. The main variable that could easily vary and could also affect the profitability of the model is the electricity buyback price, which is the price the PEA pays for electricity purchased from the farmer. It has been government policy to have an electricity buyback price that was higher than the price at which the PEA sold electricity as a way to support farmers and support renewable energy. Therefore, we analyze the effect of changes in the electricity buyback price on the IRR and payback period based on buyback prices from 0 (where the farmer is unable to sell the electricity to the grid) up to a price higher than what the farmer pays for electricity. Government pricing has a direct influence on the relative profitability of the models because the different models have different amounts of

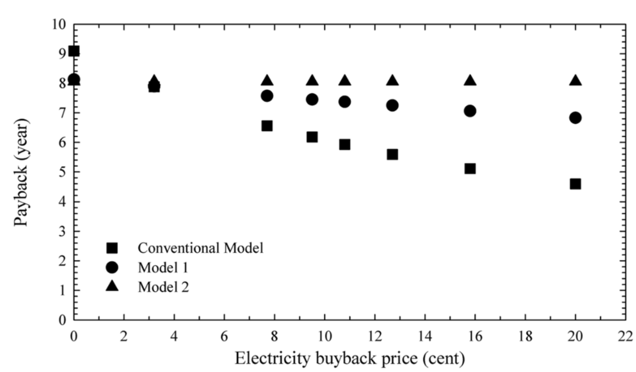


Fig. 8 Sensitivity of payback period with respect to electricity buyback price

electricity needed to be purchased and able to be sold back to the grid. This difference is particularly true since the conventional model and Model 1 have periods where excess biogas is produced, which can produce excess electricity for resale; however, Model 2 has no periods of excess production.

If the purchase price is zero, the government does not purchase electricity produced from the excess biogas, and the payback for the conventional model will then be slower than that for Model 1 and Model 2. However, when the farmer can sell electricity from excess biogas at a high price, the payback period is shorter for the conventional model than for Model 1 and Model 2. However, it is important to note that this calculation does not include installation of systems required for the resale of the electricity produced from the excess biogas.

Environmental Analysis

In the case where the surplus biogas could not be sold, it would be burned off into the atmosphere and result in air pollution, particularly the release of CO_2. By conventional management, the farm would annually release over 14,714 m^3 of biogas (12,043 kWh) into the atmosphere. Considering this in terms of CO_2 equivalent, such emissions were calculated as 19,127 m^3 CO_2 equivalent emitted per year to the atmosphere. By using the proposed management methods (Models 1 and 2, respectively), as the excess biogas could be reduced to 3043 m^3/year and zero (79–100% reduction), greenhouse gas (GHG) reductions of 9440 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 emissions due to a large decrease in excess biogas. In addition, Model 2 could most effectively lower the farming expense caused by electricity purchase.

Conclusions

The current conventional batch management method results in an imbalance between the produced biogas and the farm's energy consumption. The amount of biogas produced during high energy demand was deficient, causing undesired extra electricity expenses. In addition, at some other point in the operation, biogas was produced at a high rate when demand was low, 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 conventional management were eased by the resulting stable biogas and electricity production. Owing to the different energy demands obtained from each model, the purchased electricity could be reduced by 36 and 44%, and the excess biogas was reduced by 79 and 100% in Models 1 and 2, respectively.

The results of the analysis show that the values of IRR, PI, PP, and LCOE are approximately 9.10–10.86%, 1.24–1.40, 8.06–9.09 years, and 8.29–9.11 cents/kWh, respectively. The application of the developed models from this study to other conventional swine farms would contribute to great reductions in GHG emissions and electricity expenses.

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