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Fabrication and Performance Assessment of Desulfurizing Systems for Large-Scale Biodigesters in Cambodia

Lyhour Hin[1, 2, *], Lytour Lor[1, 2], Dyna Theng[1, 2], Chan Makara Mean[1, 2], Sovanndy Yut[1, 2], Mengchhay Kim[1, 2], Sokhom Mech[2], Gerald Hitzler[1]

[1]Faculty of Agricultural Biosystems Engineering (FABE), Royal University of Agriculture (RUA), Phnom Penh, Cambodia

[2]Biogas Technology and Information Center (BTIC), Royal University of Agriculture (RUA), Phnom Penh, Cambodia

Email address:

hlyhour@rua.edu.kh (Lyhour Hin)

[*]Corresponding author

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Abstract: Commercial pig farms in Cambodia produce great amounts of wastewater. To convert wastewater into energy, many farms have installed simple covered lagoon digesters. However, most biodigesters lack desulfurizing systems to reduce H_2S present in biogas for smooth generator operation. Desulfurizing systems are not available locally and must be imported from abroad. They are expensive, while after-sale service is hard to find. These factors may lead reluctancy to fully invest in biogas systems. Therefore, this paper aimed to compare biogas quantity and quality between two desulfurizing systems, to analyze electricity generation and generator efficiency, and to perform economic assessment of the desulfurizing systems. The study was conducted on two large-scale pig farms in two different periods. The first period was with a pig farm of 20,000 fattening pigs and 6,000 sows in Preah Sihanoukville Province, from October 2021 to July 2022. The second period targeted a pig farm of 5,000 fattening pigs and 600 sows in Kampong Thom Province between May 2022 and May 2023. The results show that biogas quantity was greater with the first farm because it had more pigs. CH_4, CO_2, and O_2 were not different before and after desulfurization for each desulfurizing system. CH_4 measured on the farm that used the Chinese desulfurizing system was 52.1%, much lower than the farm with the BTIC desulfurizing system (62.9% CH_4) due to high O_2 concentration inside the biogas pipe. H_2S was affected by desulfurization and reduced to lower than 100 ppm, which is good for generator operation. Due to larger generator size, the first farm produced greater output power (276 kW), when compared to the second farm that had output power of 125 kW. Higher generator efficiency was also observed on the first farm, but loading rate was similar for both farms. Depreciation costs for the Chinese desulfurizing system were 3,375 USD/year, being 4.3 times higher than those of the BTIC prototype (787.5 USD/year). The size and capacity of the BTIC desulfurizing system is similar to the Chinese product. Thus, if the first farm used the BTIC prototype, huge amounts of money could be saved annually. In conclusion, the BTIC desulfurizing system had a working performance similar to that of the Chinese product, but had low depreciation costs, denoting huge savings. Further studies should focus on the dissemination of the BTIC prototype to more pig farms through collaboration with the private sector and fabricators for strong market linkage.

Keywords: Anaerobic Condition, Biogas, Covered Lagoon, Generator, Iron Pellets, Manure

1. Introduction

Pig raising is considered vital for Cambodian economy and is the main source of meat supplies inside the country because pork is consumed the most, accounting for 52.8% of all meat eaten in 2018 [1]. As a result, commercial pig production increased from 24% in 2017 to 59% in 2021, as the total pig number was over 3 million heads in that year [2]. An increase in commercial pig farms means larger wastewater generation and higher electricity demands for farm operation. One average pig produces 1.2 - 1.5 kg of manure per day, or 24 L of wastewater [3-5]. This leads to environmental concerns, so supportive policies are in place to promote farm waste management and to encourage farm owners to construct biodigesters to produce biogas for electricity production [6]. In addition, pig farms normally use a great deal of electricity due to the utilization of evaporative cooling systems to promote faster pig growth and reduce risks of disease, by providing optimal temperatures in the range of 25 – 27°C inside the barns [7]. About 30 kWh/year of electricity is required for one pig [8], Meanwhile, a study in Cambodia found that one pig needs more electricity, estimated to be around 39.7 kWh/year [9].

Besides using enormous amounts of electricity, pig farms have to pay an extremely high price of electricity, when compared to neighboring countries such as Thailand and Vietnam. According to Khmer Times (2022), Cambodia ranks 102 as the most expensive country with high electricity price [10]. About 49% of its total electricity is produced from fossil fuel [11], which can potentially lead to global warming. To cope with these issues, the use of renewable energy is placed on top of the government agenda, as stated in the 2013-2030 national green growth strategic plan [12].

In response, many commercial pig farms construct simple covered lagoons to treat wastewater and convert it into biogas to run generators for electricity production. On annual basis, one pig produces 32.7 Nm^3/head/year, so enormous quantities of biogas can be potentially produced with millions of pig heads [9]. The use of biogas systems provides many benefits such as prevention of farm disease and water pollution, reduction in electricity bill costs, creation of good-quality fertilizer, and contribution to reduction in greenhouse gas emissions [13].

In Cambodia, wastewater from commercial pig farms is commonly treated in a simple covered lagoon digester—a process of digesting organic waste under anaerobic conditions. This system is cheap and easy to operate, and its final product is biogas, which is a mixture of gases that contains methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), oxygen (O_2), water vapor (H_2O), and other substances [14]. Regardless of organic matter types, biogas contains 50 – 75% CH_4, and 25 – 50% CO_2 [15], but one study in Cambodia indicated that biogas produced from wastewater discharged from pig farms contains 52.4 – 64.5% CH_4, 26.9 – 40% CO_2, 818 – 3,295 ppm H_2S, and 0.1 – 3.0% O_2 [9]. Wastewater treated in a simple covered lagoon has a hydraulic retention time (HRT) of 30 – 45 days, depending on the lagoon size.

A simple covered lagoon digester consists of a covered lagoon used for storing wastewater, a biogas desulfurizing system for reducing H_2S present in biogas, a biogas flow meter for recording biogas flow and daily biogas use, and a biogas generator for electricity generation. When all these components are installed together, the system is considered a complete set, which is crucial for long-term biogas use [16]. To meet the demand for the construction of covered lagoon biodigesters, the government encourages local suppliers to deliver the service. Existing skills available in this country include the ability to construct a covered lagoon and modify biogas generators from liquefied petroleum gas (LPG) or diesel to biogas or a dual generator. Around 500 commercial pig farms are reported to operate across the country, and only 44 have biogas systems to treat wastewater and to generate electricity for farm use [6]. Those who have biogas systems neglect desulfurizing systems because the farm owners have no ideas about the importance of these systems, so there is no need to invest more. Actually, a desulfurizing system is considered an utmost part of the biogas system because of its ability to reduce H_2S to a recommended level, which is 200 ppm for smooth biogas generator operation [17].

Several studies found that untreated H_2S can be greater 2,000 ppm (9; 16; 18). With desulfurizing systems, H_2S is greatly reduced and can be as low as 50 ppm [16]. Thus, the use of desulfurizing systems is vital for long-term and cost-effective biogas system operation. In Cambodia, very few pig farms can afford to import desulfurizing systems, mainly from China. Without the use of these systems, the generator will break down faster than usual due to high concentrations of H_2S, which eventually makes individual farm owners subject to high operation and maintenance costs. Nevertheless, although farm owners are willing to purchase desulfurizing tanks for their biogas systems, they often face the disuse of these tanks later on because the after-sale service is far, time-consuming, and costly.

To address all these issues, any attempt or motivation of fabricators to manufacture a biogas desulfurizing system locally is key to the sustainable use of a biogas system, especially by using materials available inside the country. This may help reduce the selling price and make after-sale service easy to find and provided on time. Thus, this paper aimed (1) to compare the working performance of locally fabricated desulfurizing system with an imported product by inspecting biogas quantity and quality before and after desulfurization, (2) to compare the electricity generation and generator efficiency between the two desulfurizing systems, and (3) to perform economic assessment of using the desulfurizing systems.

2. Materials and Method

Equipment used in this research were two different desulfurizing systems, a locally fabricated prototype and a Chinese commercial product, both used for H_2S removal from biogas; biogas 5000 analyzer for inspecting biogas quality; and a power logger for measuring peak load and electricity produced by biogas generators.

As entry into large-scale pig farms was strictly prohibited, to make the study possible, two different periods were chosen. The first period started from October 2021 and July 2022, by testing the Chinese desulfurizing system on a large-scale commercial pig farm located in Preah Sihanoukville Province. At the time of research, the farm raised 20,000 fattening pigs and 3,000 sows under evaporative cooling systems, and operated a full biogas system that consisted of a simple covered lagoon (90m x 25m x 5.6 m, or 10,080 m^3), a 640-kW second-hand, pure biogas generator, a four-tank desulfurizing system supplied by Hunan Along New Energy Technology Co. Ltd., a flow meter, a discharge pond used to accept digestate released from the covered lagoon.

Meanwhile, the testing of the newly fabricated prototype was carried out between May 2022 and May 2023, starting from fabrication to pre-testing, to installation on the selected pig farm, and to data collection and interpretation. After complete fabrication, it was brought and installed on another large-scale pig farm located in Kampong Thom Province. This farm had 5,000 fattening pigs and 600 sows, using evaporative cooling systems to provide optimal temperatures for faster pig growth. The first farm also operated a biogas system to treat wastewater and produce electricity for farm use. The biogas system on this farm consists of a simple covered lagoon sized 2,560 m^3, a 296-kW second-hand LPG generator modified to purely run on biogas, a flow meter, a flare, and a discharge pond which was the size as the covered lagoon. However, a desulfurizing system was missing. To ensure the generator there work smoothly and properly, a feasibility study was conducted to check if the farm met the criteria, and when the farm was qualified enough, it was provided free of charge with a locally fabricated desulfurizing system that consists of two tanks and a cyclone, but there was no blower attached.

In this study, the farm that used the desulfurizing system imported from China was called the first farm, while the farm that used the desulfurizing system fabricated locally was called the second farm. Meanwhile, the desulfurizing system, which was Chinese product, was called Chinese desulfurizing system, and a Cambodian prototype was called BTIC desulfurizing system (Table 1).

Table 1. *Description of farms, their pig raising operation, biogas systems, and testing period.*

Farm	Type/Quantity	Description
Pig farm in Preah Sihanoukville		Called the first farm
GPS		10°53'53.1"N 103°52'59.5"E
Raising type	Full production	Piglets are produced for own farm raising
Fattening pig (head)	20,000	
Sow (head)	3,000	
Digester type	Simple covered lagoon	
Digester size (m^3)	10,080 m^3	One of many covered lagoons that accept wastewater from both fattening pig barns and sow barns
Generator type	Second-hand, pure biogas	
Generator power (kW)	640	
Desulfurizing system origin	Chinese product	Called Chinese desulfurizing system in this study
Desulfurizing system specifications	4 tanks and one cyclone with a blower	
Testing period	Oct 2021 – Jul 2022	
Pig farm in Kampong Thom		Called the second farm
GPS location		12°43'48.5"N 105°08'41.4"E
Raising type	Full production	Piglets are produced for own farm raising
Fattening pig (head)	5,000	
Sow (head)	600	
Digester type	Simple covered lagoon	
Digester size (m^3)	2,560	This pond accepts wastewater from fattening pig barns only
Generator type	Second-hand, modified from LPG to biogas	
Generator power (kW)	296	
Desulfurizing system origin	BTIC prototype	Called BTIC desulfurizing system in this study
Desulfurizing system specifications	2 tanks and one cyclone without a blower	
Testing period	May 2022 – May 2023	

Materials

A Chinese commercial desulfurizing system used in this research was a system installed on the first farm to remove H_2S, as shown in Figure 2. This farm used to have a problem with fast-deteriorating generators. The system consists of four tanks and a cyclone, weighing 1.3 tons. Each tank has a diameter of 0.9 m and a height of 2.3 m, being able to store up to 400 kg of iron pellets. To Push biogas through the system, a 3-phase, 5-kW blower is attached and has the ability to suck in biogas at a flow rate of 200 Nm^3/h. The cyclone is used to remove vapor and dust before allowing the treated biogas to reach the generator.

A desulfurizing system prototype used in this research was a design made by the Biogas Technology and Information Center (BTIC) Cambodia, part of the Faculty of Agricultural Biosystems Engineering (FABE), Royal University of Agriculture (RUA), Phnom Penh, Cambodia (Figure 2). Thus, it is called BTIC desulfurizing system and jointly fabricated by FABE in collaboration with the Don Bosco School, through technical support and advising from the BTIC. This prototype consists of two tanks and one cyclone. The whole system weighs 0.8 ton, and each tank is 0.9 m in diameter and 2.3 m tall and can store up to 600 kg of iron pellets—materials used for removing H_2S through chemical reaction. The cyclone function as a vapor and dust remover. However, it did not have a blower for pushing biogas to go through. Biogas can flow through the system by the suction force of the biogas generator. This desulfurizing system was installed on the second farm under financial support from the United Nations Industrial Development Organization (UNIDO).

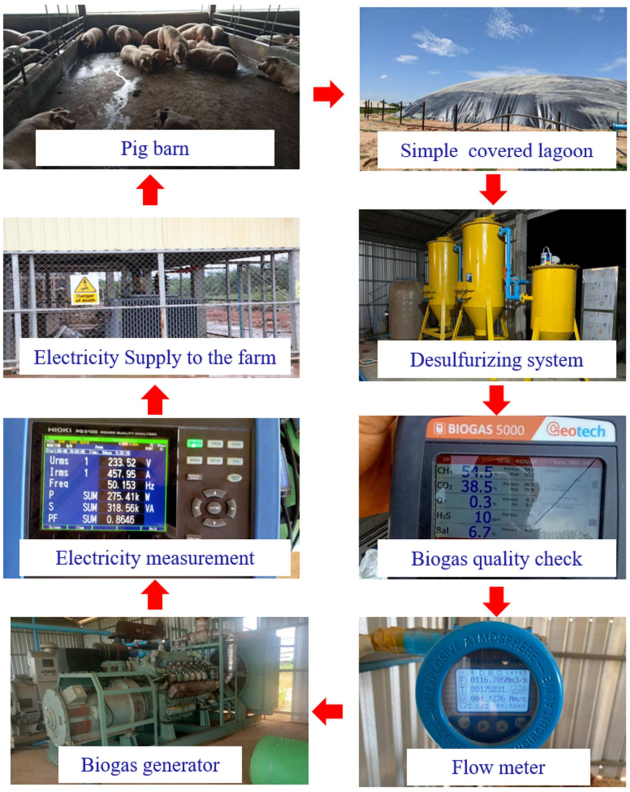


Figure 1. *Diagram of a complete biogas system starting from wastewater from pig barns to a covered lagoon until biogas produced for electriciy production and supply to the farm.*

Figure 2. *The Chinese desulfurizing system (left) installed on a large-scale pig farm in Preah Sihanoukville Province and the BTIC desulfurizing system (right) installed on a large-scale pig farm in Kampong Thom Province.*

Sampling Method

A biogas 5000 analyser was used to measure biogas quality, and it is a product supplied by Geotech, UK, while peak load and electricity consumption were measured by using Hioki PW3365-20-01/5000 power logger [9].

In this study, the data collection related to the operation of biogas system and the functionality of the desulfurizing tanks on both farms was carried out in five times with the interval of 2 – 4 weeks, as frequent travel into the farms was restricted due to concerns of African swine influenza. In each time of data collection, biogas quality was measured directly at two different locations: before and after biogas going through the desulfurizing systems. On each location, biogas was measured three times, and each measurement took two minutes. Between the sampling process, biogas that remained in the analyzer was completely flushed out before taking another sample. This process was repeated until all needed samples were obtained. Peak load and electricity consumption on both farms were measured by attaching the power logger to the electricity control panels for around one hour during the daytime, and this sampling was taken repeatedly throughout the data collection period [9].

Data Analysis and Interpretation

R program version 4.2.2 and RStudio were utilized to perform data analysis [19]. The package 'rstatix' was used to perform paired sample t-test by comparing biogas quality before and after desulfurization and two-sample t-test by comparing biogas quantity, biogas quality, output power, and generator efficiency between the two desulfurizing systems [20]. This test was applied with the error level of 5% (confidence level of 95%). The R graphic package was used to plot line graphs to observe changes in current and output power over time in about one hour of electricity measurement. Depreciation cost was also calculated and compared between the two systems, depending on the price of equipment, salvage value, and the lifespan of equipment [21].

$$Q_{biogas} = N \times MP \times DM \times BY \qquad (1)$$

Q_{biogas} represents total quantity of biogas produced daily on each pig farm. *N* is the number of pigs, while *MP* is the daily manure excreted by a pig, estimated to be 1.5 kg/head/day [3]. *DM* represents the content of dry matter present in the manure and, in this study, *DM* is 20% [22]. *BY* stands for biogas yield, which is approximately 0.33 Nm^3/kg *DM* [9].

$$PE = CF \times Q_{biogas} \qquad (2)$$

This formula was based on the study by Hin et al. [9]. *PE* is the amount of electricity potentially produced by the biogas generator, while CF is the conversion factor from biogas to electricity, in the range of 1 – 1.7, depending on the quality and age of the generator. In this study, *CF* of 1.5 was used because the generators were large in size, but second-hand. Q_{biogas} represents total quantity of biogas produced daily from each pig farm.

$$EF = P_{output}/P_{chem} \qquad (3)$$

EF represents the generator efficiency (%), while P_{output} is the actual power (kW) measured from the generator. P_{chem} represents the power (kW) chemically produced by the internal combustion of biogas. P_{chem} is equal to hourly biogas flow rate multiplied by the net calorific value (NCV = 20 MJ/Nm^3 biogas with 60% CH_4) and divided by 3600 [16].

$$LR = P_{output}/GP \qquad (4)$$

LR represents the loading rate of the generator (%), while P_{output} is the actual power (kW) measured from the generator. *GP* is the total power shown on generator specifications (kW).

$$D = (PV - SV)/L \qquad (5)$$

D represents depreciation cost of machinery or equipment (USD/year), while PV is the present value of machinery (USD), and SV is the salvage value (USD). L represents the lifespan of the machinery (year). In this study, SV is assumed to be 10% of PV *and* L is 8 years.

3. Results and Discussion

Biogas Quantity and Quality

Table 2 compares daily biogas production, hourly biogas consumption by the generators, and the operating time of the generators on the two farms that used different kinds of desulfurizing systems. Because the first farm had more pigs, biogas production was also higher. On daily basis, about 1,980 Nm^3 of biogas was produced, which was 4 times greater than the second farm. The generator used on the first farm was 640 kW, 2.2 times greater than that of the second farm, so it needed more biogas for proper operation. In this case, biogas flow rates for the generators on the first and second farms were 221.6 and 114.5 Nm^3/h, respectively. With the amount of biogas produced, the first farm could operate its generator for 8.9 hours, while the second farm could operate only for 4.3 hours. The finding in this research was lower than the studies [22, 23], whose findings were that the operating time of the generators was half a day, or 12 hours, and 65% of total electricity demand, or 15.6 hours, respectively. The reason that biogas produced on the second farm was used up much more quickly is because the electricity produced from biogas was supplied to the whole farm, also covering sow barns, while the wastewater used for biogas production was discharged from the fattening pig barns only. Meanwhile, wastewater discharged from the sow barns was stored inside a different covered lagoon, the biogas pipelines of which were not yet connected to the generator. Therefore, all biogas pipelines should be connected to have more biogas for the generator, so that a longer operating time of the generator could be obtained, and more electricity produced.

Table 2. *Comparison of Biogas quality before and after desulfurizing system.*

Biogas quality	Chinese desulfurizing system	BTIC desulfurizing system	Ratio
Pig (head)	20000	5000	4.0
Sow (head)	3000	600	5.0
Daily biogas (Nm^3/day)	1,980	495	4.0
Biogas flow rate (Nm^3/h)	221.6 ± 4.2	114.5 ± 3.0	1.9
Expected time for full biogas use (h)	8.9	4.3	2.1

Biogas quality, CH_4, CO_2, H_2S, and O_2, was compared before and after desulfurization between the two different desulfurizing systems (Table 3 and Table 4). No significant differences were detected with CH_4, CO_2, and O_2 before and after desulfurization. This is common because the desulfurizing systems reduced the concentration of H_2S due to the presence of iron pellets (Fe_2O_3). Thus, there was a significant difference in H_2S when biogas was treated with iron pellets. On the first farm, CH_4, CO_2, and O_2 averaged 52.1%, 23.5%, and 4.2%, respectively, regardless of desulfurization. Similarly, on the second farm, CH_4, CO_2, and O_2 were not also affected by iron pellets, averaging 62.9%, 32.6%, and 0.6%, respectively. By using the desulfurizing systems, H_2S was greatly reduced. Before desulfurization, H_2S was 3,849.6 ppm on the first farm and 2,500 ppm on the second farm, and decreased to lower than 100 ppm after desulfurization. Normally, biogas produced from pig wastewater contains CH_4 of about 60% or higher [9; 24; 25; 26], so lower CH_4 was due to abnormally higher concentrations of O_2. As shown in Figure 3, CH_4 decreases when O_2 increases, and if O_2 is greater than 4%, CH_4 will decrease to less than 50%. Similar results were found in the studies [9; 16], who indicated high O_2 content lowered CH_4. The reason for high concentrations of O_2 is due to leakages along the biogas pipes, which enables the sucking-in of the air when the biogas generator is running. To reduce O_2, proper inspection along biogas pipelines is needed to prevent leakages. H_2S was observed to be much greater on the first farm than on the second farm, and this may be due to the type of feed fed to pigs. The higher protein the feed contains, the more H_2S is produced [18]. H_2S can be higher than 3,000 ppm when biogas is produced from pig manure [27].

Table 3. *Comparison of Biogas quality before and after desulfurizing system.*

Biogas quality	Chinese desulfurizing system			
	Before	After	Significant	Average
CH_4 (%)	51.2	52.9	ns	52.1
CO_2 (%)	22.8	24.2	ns	23.5
H_2S (ppm)	3,849.6	61.3	***	
O_2 (%)	4.2	4.1	ns	4.2

Biogas quality	BTIC desulfurizing system			
	Before	After	Significant	Average
CH_4 (%)	63.0	62.7	ns	62.9
CO_2 (%)	32.4	32.8	ns	32.6
H_2S (ppm)	2,500	87.0	***	
O_2 (%)	0.5	0.6	ns	0.6

Note: the asterisk (***) denotes statistically significant differences at $P < 0.001$, while "ns" means non-significance. With "ns", average calculation is applied.

Table 4. *Comparison of biogas quality treated by the two desulfurizing systems.*

Biogas quality	Chinese desulfuring system	BTIC desulfurizing system	Significant
CH_4 (%)	52.9 ± 5.2	62.7 ± 0.2	***
CO_2 (%)	24.2 ± 3.6	32.8 ± 1.1	***
H_2S (ppm)	61.3 + 1.2	87.0 + 0.8	ns
O_2 (%)	4.1 ± 1.0	0.6 ± 0.1	***

Note: the asterisk (***) denotes statistically significant differences at $P < 0.001$, while "ns" means non-significance.

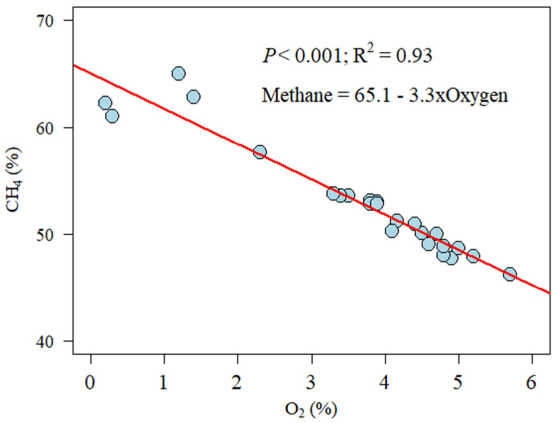


Figure 3. *Relationship between CH_4 and O_2.*

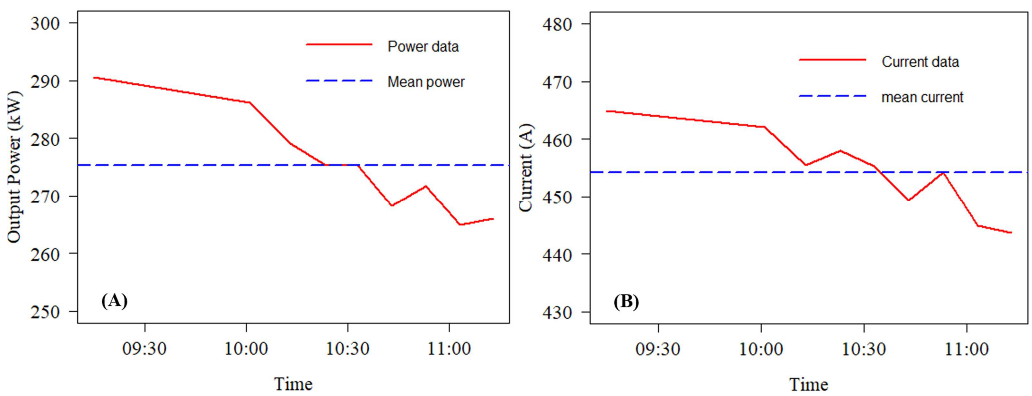
Power Generation and Generator Efficiency

Figure 4 compares current and output power produced by the generators on both farms. On the first farm, current and output power were measured from 9:00 am to 11:20, while the measurement was done between 13:00 and 14:00 on the second farm. It can be seen that the output power and current had a downward trend on the first farm, while these parameters fluctuated and increased until 14:00 on the second farm. In both cases, the output power and current on the first farm was 276 kW and 454 A on average, respectively. On the second farm, they averaged 125 kW and 237 A, respectively. Because both farms had different numbers of pigs, so total current and output power also differed. However, with the number of pigs and output power obtained from both farms, it can be estimated that average output power per pig head was 0.01 kW/head for the first farm and 0.03 kW/head for the second farm. With this figure, it can be concluded that the first farm was more efficient in terms of electricity use.

Power, generator efficiency and loading rate were compared between the two farms that utilized different desulfurizing systems (Table 5). With a larger generator, the first farm produced more power, had higher generator efficiency, but had a similar loading rate. On daily basis, potential electricity production was 2,970 and 743 kWh/day on the first second farms, respectively. Chemical power was 1,050.5 and 664.7 kW on the first and second farms, respectively. Higher generator efficiency was seen with the generator used on the first farm, being 25.7%. Meanwhile, it was around 18.1% for the second farm. Regardless of the generator size, the loading rate was around 41-42%. Mean et al. (2022) who also studied a biogas system in Cambodia found higher generator efficiency (26.8%) and greater loading rate (57.6%), and this is because the studied farm had the pig number almost two times greater than the first farm. However, this study had very low generator efficiency, when compared to the research by Peerapong and Limmeechokchai [26], whose finding was 40% with a 435-kW generator. The reason is that they used a new pure biogas generator that is capable of having a better performance.

Table 5. *Comparison of electricity production, generator efficiency, and loading rate by the two desulfurizing systems.*

Item	Chinese desulfurizing system	BTIC desulfurizing system
Generator size (kW)	640	296
Electricity production (kWh/day)	2,970	743
Output power (kW)	276	125
Chemical power (kW)	1,050.5	664.7
Generator efficiency (%)	25.7	18.1
Loading rate (%)	42	41



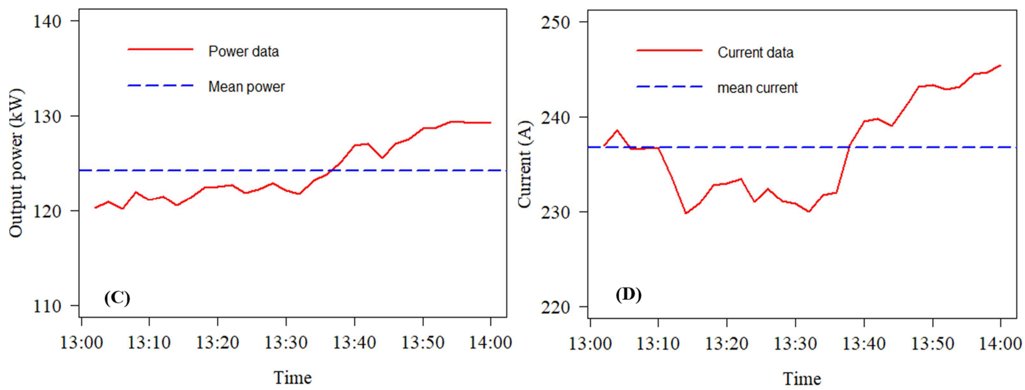


Figure 4. *Changes in electricity current and power measured over time on the two farms. Changes in current (A) and and output power (B) on The first farm with the Chinese desulfurizing system and changes in current (C) and output power (D) on the second farm with the BTIC desulfurizing system.*

Economic Analysis

Table 6 compares depreciation costs for the two desulfurizing systems. In this study, the salvage value was 10% and the lifespan of both generators was 8 years. Therefore, the depreciation cost was 3,375 and 787.5 USD/year for the generators used on the first and second farms, respectively. Much higher depreciation cost was observed with the Chinese desulfurizing system, but the BTIC desulfurizing system has the similar size and capacity of storing iron pellets for chemical reaction with biogas to reduce H_2S. Thus, if the first farm also used the BTIC desulfurizing system, great amounts of money could be saved and after-sale service might be more available, thereby bringing much more benefits to the farm.

Table 6. *Comparison of depreciation cost between the two desulfurizing systems.*

Item	Chinese desulfurizing system	BTIC desulfurizing system	Ratio[a]
Original price (USD)	30,000	7,000	4.3
Salvage value (USD)	3,000	700	
Lifespan (year)	8	8	
D (USD/year)	3,375	787.5	4.3
D/head (USD/head/year)	0.2	0.2	

a: Ratio is equal to values in column 2 divided by those in column 3.

4. Conclusion

This study focused on the testing of two different desulfurizing systems: a Chinese commercial product and a locally fabricated prototype. Two large-scale pig farms that had biogas systems were the target. It was found that both desulfurizing systems could potentially reduce H_2S to a recommended level for biogas generator operation. However, other biogas components such as CH_4, CO_2, and O_2, were not affected by desulfurization. CH_4 was affected by high concentrations of O_2, which may penetrate into the biogas system through leakages in the pipelines. In terms of performance, the BTIC desulfurizing system also had a desirable working performance considered similar in quality to the Chinese desulfurizing system. Because the BTIC prototype was fabricated locally and was much cheaper, so the depreciation costs were also lower. This finding is highly significant when the capacity of both systems is the same, so using the BTIC prototype is more economical and more convenient due to easy access and fast after-sale service. Future studies will continue testing the BTIC prototype with several more pig farms to doublecheck the performance to showcase the result to pig farm owners, and this work can be done through collaboration with the private sector and fabricators to ensure the prototype can multiplied and linked to the market.

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