Enhancement of household biogas production by solar collector and solar greenhouse

Rotjapun Nirunsin[1], Worajit Setthapun[1], Natthawud Dussadee[2] and Hathaithip Ninsonti[1,*]

[1] Asian Development College for Community Economy and Technology,
Chiang Mai Rajabhat University, Thailand.
[2] School of Renewable Energy, Maejo University, Thailand
***Corresponding author:** hathaithip.nin@gmail.com

Abstract

The objective of this study is to enhance the biogas production by increasing the temperature of the digested slurry inside the biogas digester to be within the appropriate range (37±2°C). Two solar heating techniques including solar collector and solar greenhouse were applied and compared in this study. Operational parameters of biogas production were kept under the same condition such as the feeding material with Organic Loading Rate (OLR) 5.6 kg COD/m^{3}organic waste; Hydrolic Retention Time (HRT) is 10 days; digested slurry was mixed for 10 min every 3 h; and the experimental data were recorded every hour during 12:00 am till 12:00 pm. The experimental results showed that use of solar collector technique was able to increase and maintain temperature of digested slurry inside the biogas digester and was within the proper range, continuously. While solar greenhouse was able to increase temperature of digester slurry as well as solar collector technique but temperatures were mostly higher than the proper range of anaerobic operational temperature. Furthermore, total biogas production quantity when using solar collector and solar greenhouse were 368.60 L/kg $COD_{removed}$ and 234.99L/ kg $COD_{removed}$ respectively, while total biogas production quantity without using solar heating was 100.31 kg $COD_{removed}$. In addition, the ratios of biogas production when using solar collector and solar greenhouse, as compared to biogas production without solar heating, were 3.9 and 2.4, respectively. As a result, solar collector technique is the most effective method to enhance the biogas production from anaerobic fermentation process.

Keywords: *household biogas, solar collector, solar greenhouse*

1. Introduction

Due to the increasing prices of fossil fuels and energy sources, finding alternative, clean and economical sources of energy has nowadays become a major concern for households and nations' economies. The implementation of renewable energy has a great potential of mitigating several problems related to ecological imbalance, crucial fuel demand, health and quality of life in rural and semi-urban areas [1]. The biogas technology is a key for environmental pollution control because methane is an important greenhouse gas which could act as a good renewable energy source. The performance and efficiency of the anaerobic digestion process is dependent on substrate temperature, available nutrients, retention time, nitrogen inhibition and C/N ratio, substrate solid content and agitation, pH level and inhibitory factors [2–3].

However, temperature is an important factor that may affect the performance of anaerobic digestion [4]. The amount of gas produced increases with digester temperature, with retention time and with the percentage of total solid in the slurry. Most of anaerobic digesters in Thailand are commonly designed to operate in the mesophilic temperature range, between 20–40 °C [5]. However, in the northern part of Thailand temperature drops lower (<20 °C) than the mesophilic temperatures during winter. Solar is a high potential energy resource in the northern Thailand, which can be used to increase anaerobic digestion temperature. The utilization of solar energy doesn't only achieve high digestion rates and process efficiency, but is also environment friendly and economical. Heating of biogas digester to a temperature of 37±2°C is important for mesophilic bacteria's growth and activity in order to increase biogas production [5–7]. Energy is required for this process and researchers must find ways to supply the necessary energy at minimum cost. The other problem encountered for such a biogas digester is the ability to control the temperature and to minimize its range of variation so that the activity of bacteria will not significantly be affected [8].

This study involves utilization of solar thermal energy to heat the digested slurry inside the biogas digester by using 2 techniques namely solar collector and solar greenhouse. The first technique is solar collector combined with heat exchanger and the second technique is solar greenhouse designed to cover the biogas digester to collect the solar thermal energy. These two techniques were utilized to warmup the digested slurry inside the biogas digester for increasing the anaerobic digestion temperature to the proper range. Finally, the comparisons of efficiency of the biogas production from using these solar heating techniques were presented.

2. Experimental setup

The experiments were conducted using the 1,000 L biogas production system. Biogas production from the fermentation process with anaerobic bacteria under ambient condition was studied. The diagram of biogas production plant used in this research is shown in Figure 1. Solar heating techniques of solar collector and solar greenhouse were applied and compared. For the enhancement of biogas production, solar collector panel was connected to 1,000 L biogas digester system. In the case of biogas production enhancement using solar greenhouse, a solar greenhouse was used to store heat energy from the solar and it was built to cover the entire 1,000 L biogas digester system so that the heat energy get transferred to digested slurry inside the biogas digester.

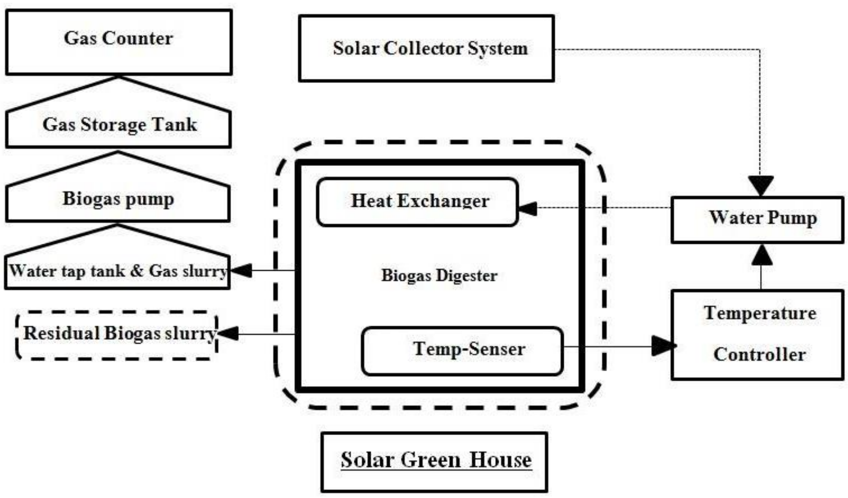


Figure 1 Diagram of biogas production under anaerobic fermentation process

2.1 Materials and equipment

2.1.1 1,000 L biogas production system

1,000 L biogas production system consists of a 1,000 L biogas digester, a biogas storage tank that stores biogas with a water replacement technique, a water trapping tank, a biogas pump, a biogas compression tank, a pressure-regulator valve with a moisture filter, a biogas counter, a circulation pump, an electrical controller system that automatically controls biogas compression, and a biogas stove, as shown in Figure 2.

Figure 2 The 1,000 L biogas production system

2.1.2 Solar collector heating system

Solar collector heating system, as shown in Figure 3, has a 218x127 cm^2 solar collector panel as the main component and produced hot water is stored inside a 200 L water tank, which has a temperature gauge to display temperature level of hot water inside. Temperature of water in the hot water tank is measured continuously for operation of the hot water pump, as shown in Figure 3. Hot water will be circulated inside the digester through a 14 m long and 5/8 inch diameter copper tube. 2.77 L of hot water could be circulated through this tube for heat exchange between hot water and digested slurry. The circulation rate of hot water is fixed at 0.5 L/min in order to maximize the heat transfer.

Figure 3 Solar collector connected to 1,000 L biogas digester system

Operation of the automatic hot water circulation system starts when the controller receives electrical signals from the temperature sensors are installed at the outlet of hot water tank and inside the biogas digester. The hot water pump operates under a condition that the temperature of hot water in the tank must not be lower than 45 °C and the temperature of digested slurry must be lower than 37 °C. This 45°C temperature is high enough to compensate for the loss of heat energy in the tube and still allows the heat to be transferred to digested slurry inside the biogas digester. Unless this condition is met, the hot water pump will not be operated.

2.1.3 Solar greenhouse heating system

Solar greenhouse was used as another technique to raise the temperature of digester. The operational principle of this system is based on the increase of temperature inside solar greenhouse which is expected to warm the digested slurry inside the biogas digester to a level that is appropriate for functioning of anaerobic digestion process. Solar greenhouse used in this research is shown in Figure 4. It was designed to be 2.10 m wide, 3 m long and 2.20 m high with an arched roof style. The entire solar greenhouse was covered with 0.2 mm. thick UV protection plastic sheets; however a door like opening was made to provide access for data collection and maintenance.

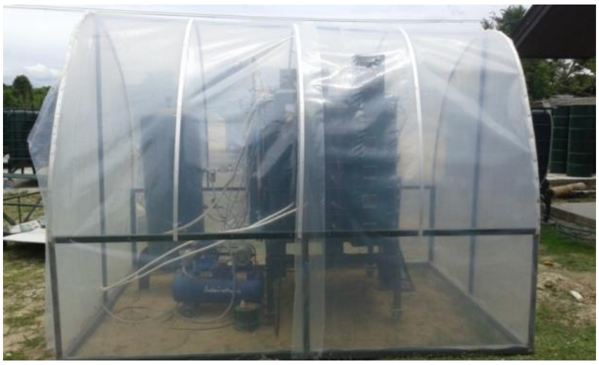


Figure 4 Solar greenhouse covering the entire 1,000 L biogas digester system

2.2 Experimental procedure

2.2.1 The innoculum for this experiment was 400 L of digested slurry from a biogas production system which contains effective anaerobic bacteria. It was filled into the 1,000 L biogas digester. The digested slurry was then left inside the digester for 2 weeks. During this period, any gas produced was released.

2.2.2 The feeding material (organic waste) was prepared 100 L for batch fermentation. The process started from taking 50 kg of organic waste material that was grinded finely with a grinder, mixed with water and the total volume of feeding or slurry was kept 100 L. The well–mixed material was then poured into the biogas digester.

2.2.3 Operation of the circulation pump was timed to operate for 10 min every 3 h to allow the digested slurry to mix well with the organic waste material.

2.2.4 Temperature of digested slurry is measured in 3 vertically–arranged positions, i.e., at the bottom of the digester, at the middle of the digester, and under the surface of the digested slurry. Quantity of the occurred biogas, pH values of the digested slurry, temperature of the environment (ambient temperature), composition of the biogas, and light intensity were measured. These data were recorded every hour during the whole experimental period of 10 days [9].

2.2.5 The experiments with 3 conditions were conducted, i.e., biogas production under ambient condition (without solar heating), biogas production under solar collector heating and biogas production under solar greenhouse heating.

3. Experimental results and discussion

This research was about the use of heat from solar energy to increase the temperature of biogas digester so that the anaerobic bacteria can perform the fermentation process more efficiently. Two techniques of solar energy were applied, i.e., using a solar collector to produce heat and using a solar greenhouse for storing heat energy. The results from these techniques were compared with the results of the experiment conducted without solar heating technique. The light intensity and ambient temperature were measured for all experimental conditions, as shown in Figure 5 and 6. According to the results, the trends of light intensity and ambient temperature of each experimental condition are similar. Light intensity and temperature at the same time of day are similar for all conditions. That means the amounts of solar energy, as the source of heat, for all three conditions were not different. Thus, the difference in gas production was only affected by the techniques of solar energy utilization for warming up digested slurry inside the biogas digester.

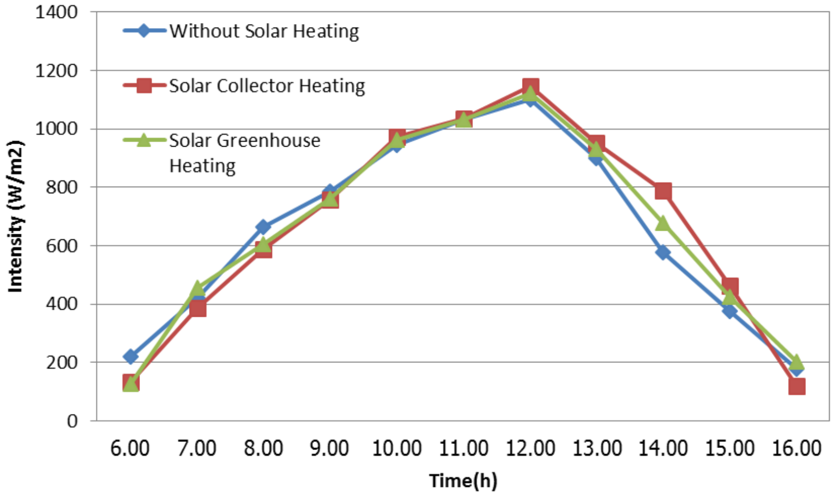


Figure 5 Comparison of light intensity among three experimental conditions

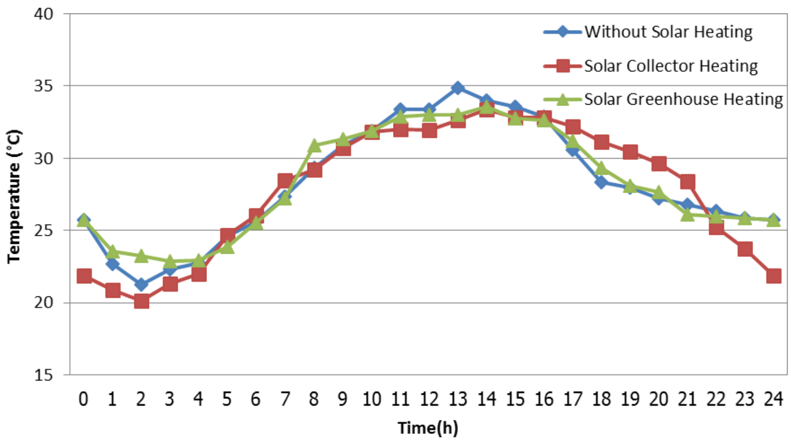


Figure 6 Comparison of the ambient temperature among three experimental conditions

In addition to temperature, pH values of digested slurry and the analyzed compositions of biogas that occurred from the fermentation process of anaerobic bacteria were studied as shown in Table 1. The biogas production occurred under the pH range of digested slurry during the experiment at 7.0–7.2 [10]. It could be seen that pH values of digested slurry were at a moderate level for all three conditions. This neutral–pH condition is suitable for functioning of bacteria. When compositions of the produced biogas was analyzed, as shown in Table 1.The highest methane yield from solar collector heating, solar greenhouse heating and without solar heating technique were 58%, 55% and 51%, respectively [11, 12]. It was found that the organic waste material fermentation when using solar collector heating yielded the purest methane gas, followed by those of using solar greenhouse heating and without solar heating, respectively. Quantities of CO_2 and N_2 in biogas were corresponding with the values as shown in Table 1. The proportion of H_2S was very low for each condition because the feeding material for biogas production in this research was from organic waste material. This result is different from biogas produced from fecal matter of animals, which would contain a very high ratio of H_2S. It is known that high H_2S could damage metallic parts inside the biogas production system [13].

Table1 A comparison of biogas composition, pH and total biogas production amount among three experimental conditions

Experimental conditions	Biogas compositions				pH	Total biogas production quantity (L)
	CH_4 (%)	CO_2(%)	N_2 (%)	H_2S (ppm)		
Without solar heating	48–51	40–47	2–13	0.3–2	7.1–7.3	956
Solar collector heating	55–58	33–42	2–10	0.3–2	7.0–7.2	3,754
Solar greenhouse heating	51–55	36–45	2–11	0.3–2	7.0–7.2	2,325

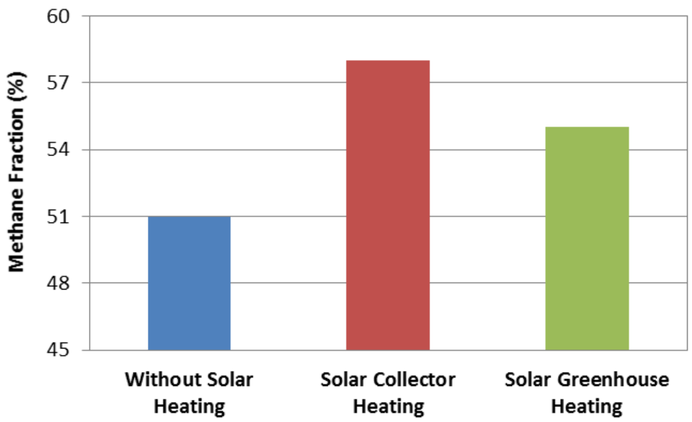


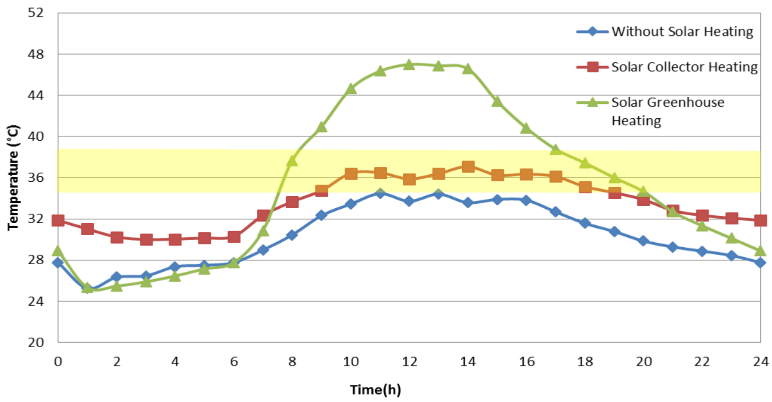
Figure 7 A comparison of highest methane yield of three experimental conditions

Temperature of digested slurry was measured at the bottom of the digester, at the middle of the digester and under the surface of the digested slurry as shown in Figure 8(a), 8(b) and 8(c), respectively. Figure 8(a) shows the temperature of digested slurry at the bottom of the digester. The appropriate temperature range of digested slurry should be within 37±2 ºC, which is presented as the yellow area. Temperatures of digested slurry when using both solar collector heating and solar greenhouse heating were within this appropriate range while a condition of without solar heating showed that the temperature was lower than the appropriate range. Solar collector heating maintained the temperature within the appropriate range continuously from 9: 00 am till 7: 00 pm. For solar greenhouse heating, there were only certain short periods of time (during 7:00 am till 8:00 pm and during 5:00 pm till 8:00 pm) where the temperature was in the appropriate range. From 8:00 am till 5:00, the temperature went up higher than the appropriate range. By the way, there were some periods that the temperature was still within the functional range of mesophilic bacteria (between 20 and 45 °C). However, during 11:00 am till 2:00 pm, the temperature went up to be in the range of 46–47 °C, which exceeds the mesophilic range. Then, after 2:00 pm, the temperature returned back within the mesophilic range until the end of the experiment, as shown in the Figure 8(a).

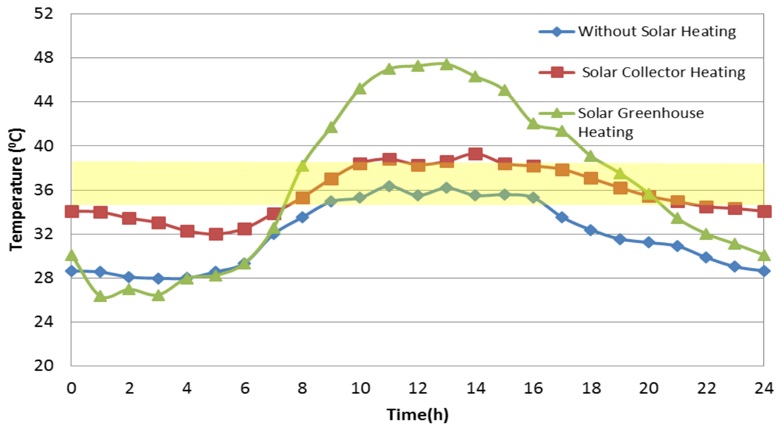
A comparison for temperature of digested slurry at the middle of the digester for three conditions, as shown in Figure 8(b) revealed that all conditions had some time periods in the appropriate temperature range. The conditions could be ordered according to the length of time of proper temperature range, from longer to shorter time, as solar collector heating, without solar heating and solar greenhouse heating, respectively. For condition of solar greenhouse heating, there was a period of time when the temperature was higher than the mesophilic range.

A comparison on temperature of digested slurry in the biogas digester under the surface of the digested slurry among the three conditions, as shown in Figure 8(c) showed that solar collector heating was found to be able to maintain temperature within the appropriate range for the longest period of time, corresponding to other measured positions. The difference occurred only during 9:00 am to 3:00 pm, when the temperature was just slightly higher than the appropriate range. After that, the temperature returned back within the appropriate range until the end of the experiment at 12:00 pm. In the condition of without solar heating, its curve is similar to the representing curve in Figure 8(b). When using solar greenhouse heating, there was a period when the temperature was much higher than the mesophilic range and reaching the thermophilic range (50–60 °C) [14], which was during 12:00 am till 1:00 pm. Subsequently, the temperature went down within the mesophilic range till the end of the experiment.

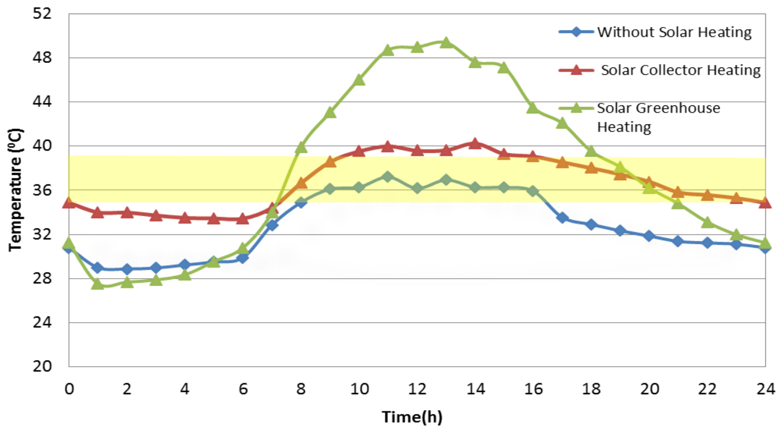
The internal temperature of biogas tank strongly depends on solar radiation and ambient temperature. It was found that, high intensity of light results in high ambient temperature. As a result, internal temperature also increases with increase in ambient temperature. For the comparison between the ambient temperature and internal temperature of 3 systems (without solar heating, solar collector heating and solar greenhouse heating), digested slurry temperature of each system were measured. It was found that, system with solar greenhouse heating showed the highest difference in temperature followed by system with solar collector heating and system without solar heating, respectively. In addition, for solar greenhouse heating system, solar greenhouse dome was made from polyethylene plastic which is a good insulator for heat. Therefore, this system could generate temperature more than the other systems.



(a)



(b)



(c)

Figure 8 Temperature of digested slurry (a) at the bottom of the digester, (b) at the middle of the digester and (c) under the surface of the digested slurry

According to the results of using heat from solar energy to increase temperature of digested slurry inside the biogas digester in this research, these techniques could increase the temperature of digested slurry within the proper range for the fermentation process of anaerobic mesophilic bacteria [15]. The effects of each solar heating technique on temperature lead to differences in organic waste material fermentation among the experimental conditions. The effects of each solar heating technique on temperature lead to differences in organic waste material fermentation among the experimental conditions that could be discussed in COD removal of each condition as shown in Figure 9 COD influent (COD_{in}) of slurry of each condition is started with a value close to that in the same range (27,894 – 28,012 mg/L). These values were appropriate for biogas system when it started up. The solar heating technique is the most effective in COD removal because the temperature was in the proper range in the long term more than other conditions. The proper range effected to anaerobic process from bacteria digestion in other hand temperature increasing of the solar greenhouse heating was stimulated bacteria on anaerobic process too but in some days was found higher temperature than mesophilic range that not appropriate for biogas system (over 40°C). Eventhough, the effectiveness of solar greenhouse heating was less than solar collector heating but still effective than no solar heating condition. The COD removal of three conditions is shown in percentage in Figure 9 and Figure 10.

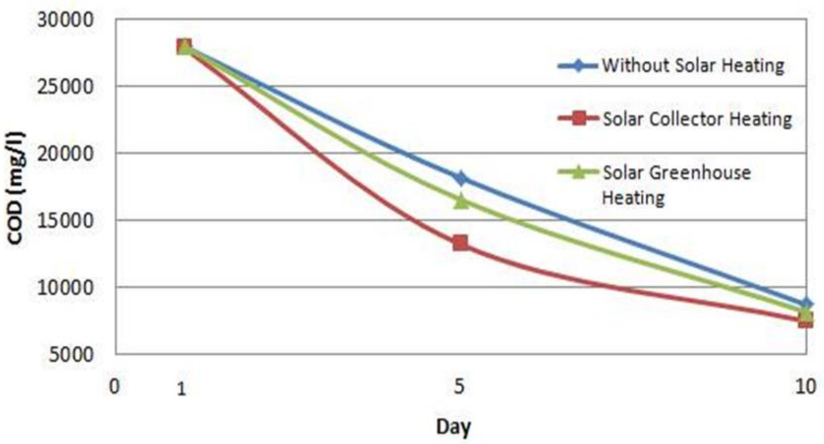


Figure 9 A comparison of COD_{in} and COD_{out} of three experiment

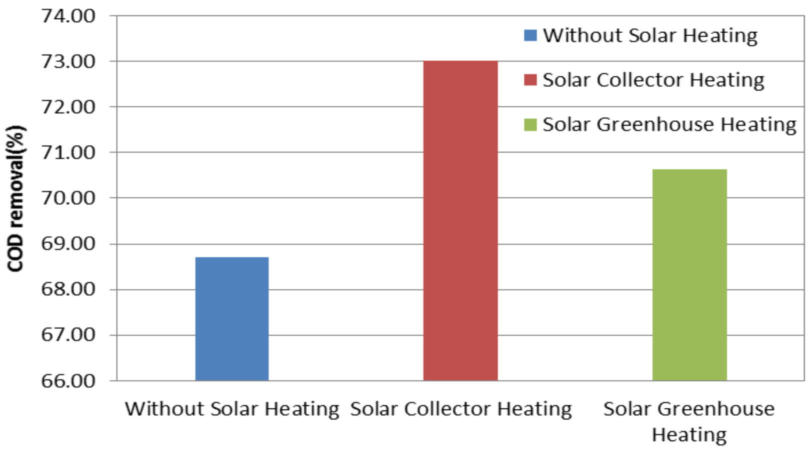


Figure 10 A comparison of highest methane fraction of each condition

The quantities of daily biogas production from each condition could be compared as shown in Figure 11. According to the result, the technique of using solar collector heating could efficiently stimulate the fermentation process of anaerobic bacteria. The quantity of biogas produced by this technique is apparently greater than those of the other technique. This is because it could control temperature of digested slurry to be within the proper range of 37±2 °C continuously [16, 17]. This allows bacteria to decompose organic waste material inside the digester effectively and continuously throughout the experimental period [13]. Moreover, there was a large amount of biogas produced during the first 3 days when using solar collector heating, as compared to the production in the remaining experimental days. This trend is different from the daily biogas production using a solar greenhouse heating. The quantity of biogas production using a solar greenhouse heating was quite consistent during the first 5 days and during the latter 5 days. Although the production during the last 5 days was lower than the first 5 days, the production in each day yielded similar quantities. This phenomenon happens even though the biogas production using a solar greenhouse heating was unable to control temperature of digested slurry in the biogas digester to be within the proper range like the use of solar collector heating. The use of a solar greenhouse heating raise the temperature at some times to fall in the upper portion of the mesophilic range, which is higher than the proper range. However, this high temperature was still able to stimulate functioning of anaerobic bacteria. Therefore, it could be operated continuously. For the biogas production without solar heating, although the temperature of digested slurry is within the mesophilic range throughout the experimental period, it was lower than the proper temperature range for fermentation process of bacteria. Therefore, the efficiency of biogas production was low. Considering the daily production, biogas quantities decreased continuously after the first 3 experimental days without solar heating. In this condition anaerobic bacteria took longer time to decompose organic waste material than the other two techniques which utilize solar energy to raise temperature of digested slurry inside the digester. The two solar heating techniques were found to be effective in enhancing biogas production and reducing retention time (the time required for fermentation of organic matter in each cycle). That means the solar heating techniques allow faster input feeding of organic waste material in the next cycle while increasing effectiveness in removal of organic waste material in the digester.

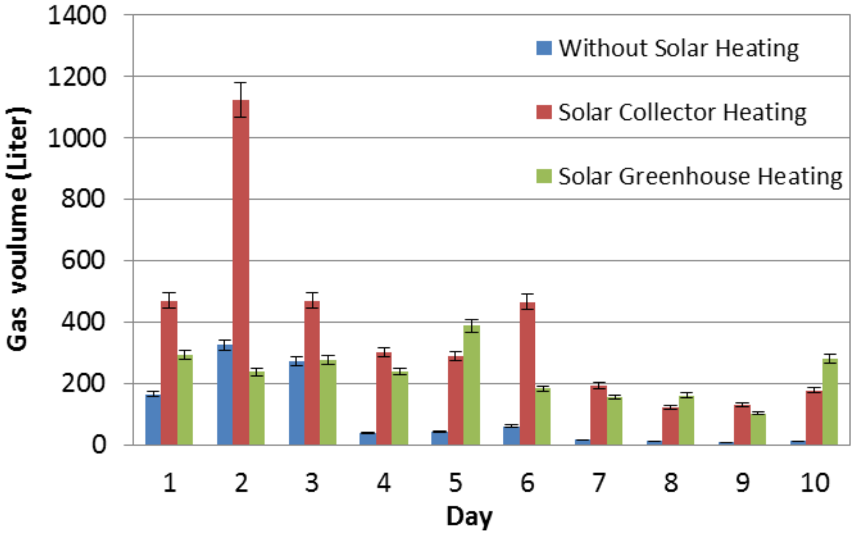


Figure 11 Quantities of daily biogas production of three experimental conditions

A comparison among the accumulated quantities of biogas from the three conditions, as shown in Figure 12, revealed that biogas production was highest with solar collector heating, followed by solar greenhouse and production without solar heating, respectively. The technique of using solar collector heating to raise temperature of the system resulted in the maximum accumulated quantity of 3,754 L (368 L/kg $COD_{removed}$) which is 3.9 times higher than the quantity of biogas production without solar heating condition. Similarly, the technique of using solar greenhouse heating to increase temperature of the digested slurry yielded, the maximum accumulated biogas quantity of 2,325 L (234.99 L/ kg $COD_{removed}$) which was 2.4 times higher than the production without solar heating condition.

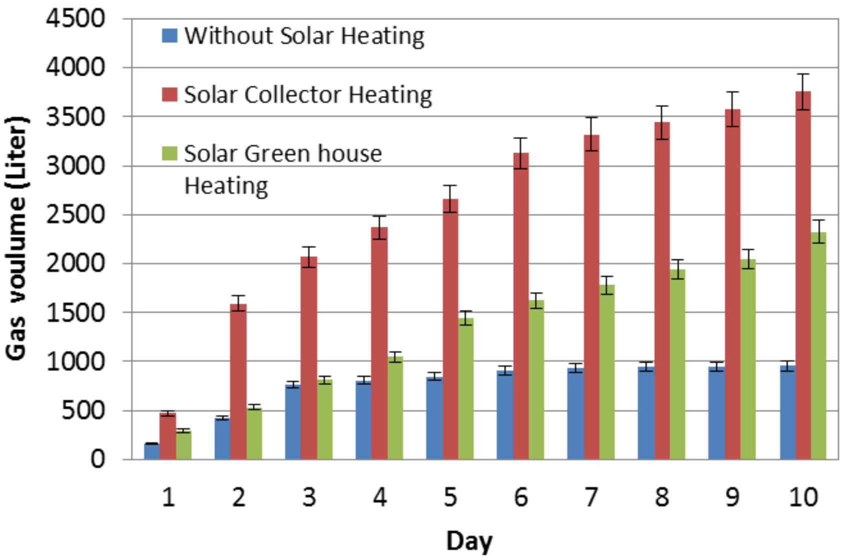


Figure 12 Quantities of accumulated biogas production of three experimental conditions

Biogas production using solar collector heating was more efficient than using solar greenhouse heating since it could control the temperature within the proper range continuously for a longer time. By the way, it is a complicated technique that requires much more expensive equipment than solar greenhouse heating. Therefore, it is quite impractical to be applied by ordinary users. Thus, the technique of raising temperature by means of heat–storing solar greenhouse is more interesting and more practical. The experimental results also showed that this solar greenhouse technique could stimulate the fermentation process of anaerobic bacteria to take place consistently and more efficiently than the fermentation occurs without solar heating [18, 19]. Although the average temperature of Thailand is within the mesophilic range, the results show that fermentation of organic waste material by anaerobic bacteria under the ambient temperature occurred mostly under the proper temperature range (37±2 °C). Even though the temperature was not lower than 20 °C, which is the minimum temperature of the mesophilic range, the biogas production would be better if the temperature could be increased up to the proper range or higher than that. Under proper or high temperature, efficiency of organic waste material fermentation can be higher for 2.4–3.9 times [20], which is in agreement with the experimental result as presented previously.

4. Conclusion

Three experiments under 3 conditions have been conducted to test efficiency from the use of solar heat for raising temperature of digested slurry inside a 1,000 L biogas digester to achieve higher efficiency of organic waste material fermentation and better biogas production. Two solar energy based techniques namely a solar collector and a solar greenhouse were applied. The results could be concluded as follows.

4.1 The technique of increasing temperature of digested slurry via a solar heat production system relied on a 218x127 cm^2 solar collector and a 200 L hot water tank. The temperature of digested slurry was increased via a heat transfer process by allowing circulation of hot water through a 5/8 inch diameter and 14 m long copper tube. This technique could increase the temperature of digested slurry within the proper range of 37±2 °C continuously.

4.2 The technique of increasing temperature of digested slurry by using a heat–storing solar greenhouse relied on a greenhouse measuring 2.10 m width, 3.00 m length, and 2.20 m height. The solar greenhouse heating system was prepared by covering the plant entirely with 0.2 mm thick UV protection plastic sheets. This allows the temperature of digested slurry inside the biogas digester to be increased. However, the temperature was increased higher than the proper range, and this technique could not control the temperature within the proper range continuously. There were only some short periods of time when the temperature remained within the proper range.

4.3 The accumulated quantity of produced biogas without solar heating condition was 965 L (100.31 kg $COD_{removed}$), while the solar collector heating produced biogas in total 3,754 L (368.60 L/kg $COD_{removed}$), and solar greenhouse heating yielded an accumulated biogas production of 2,325 L (234.99 L/ kg $COD_{removed}$). The ratios of biogas production from the solar collector heating and solar greenhouse heating as compared with the without solar heating are equal to 3.9 and 2.4, respectively. That means the use of a solar collector panel to store heat energy and increase temperature of digested slurry was the most efficient technique for biogas production. The reason is this technique could maintain the temperature of digested slurry to be within the proper range more continuously and more consistently than the technique of using a solar greenhouse heating.

4.4 The results from the analysis on compositions of the produced biogas reveal that biogas produced from the solar collector heating had the highest quality. Biogas from this technique contained 55–58% of methane, 33–42% of carbon dioxide, 2–10% of nitrogen and 0.3–2 ppm of hydrogen sulfide. The average of methane fraction for 10 days is 56.4 % and the maximum is 58%. The biogas production occurred under the pH range of digested slurry during the experiment at 7.0–7.2.

4.5 The results of COD removal reveal that COD removal from the solar collector heating had the highest percentage. It was 73.02% because the temperature was in the proper range in the long term.

4.6 The experiment results represent only winter period, in summer at higher ambient temperatures the temperatures may rise further for the Green House case, however it will contribute to get better results in the case of no solar heating as compared to winters.

Acknowledgement

The researcher would like to thank you for the financial support from Energy Policy and Planning Office, Ministry of Energy and Defense Energy Department for the research equipments. In addition, we would like to thank Asian Development College for Community Economy and Technology (adiCET), Chiang Mai Rajabhat University and School of Renewable Energy, Maejo University for providing analysis tools for this research.

References

[1] Rahman M, Mottalib M and Bhuiyan MA, "Study on biogas technology in Bangladesh," 22nd WEDC Conference Reaching the Unreached Challenges for the 21st Century; New Delhi; India (1996).
[2] Information and Advisory Service on Appropriate Technology (ISAT), "Biogas digest–Biogas basics," German Agency for Technical Cooperation, 1 (1999).
[3] Dennis A and Burke PE, "Dairy waste anaerobic digestion handbook," Environmental Energy Company, Olympia (2001).
[4] El–Mashad HM, Van L, Wilko KP, Zeeman G, Bot PA and Gerard Lettinga G, "Design of a solar thermophilic anaerobic reactor for small farms," Biosyst Eng, 87 (2004) 79–87.
[5] Hu J etc, "Theories and techniques of anaerobic wastewater treatment [M]," Building Press China, Beijing, China (2003).
[6] Ren N and Wang A, "Principles and applications of anaerobic biotechnology," Chemical Industry Press, Beijing, China (2004).

[7] Zhenjie R, Zhili C, Li–an H, Wenbiao W, Kaisheng X, Xiao X and Wantu Z, "Design investigation of a solar energy heating system for anaerobic sewage treatment," Energy Procedia, 14 (2002) 255–259.
[8] Alkhamis TM, El–Khazali, R , Kablan, M and Alhusein MA, "Heating of a biogas reactor using a solar energy system with temperature control unit," Sol Energy, 69 (2000) 239–247.
[9] Kartihik R, Solmaz A and Mohammad JT, "Household biogas digesters–A review," Energies, 5 (2012) 2911–2942.
[10] Yaug LiG and QU YF, "Control factors of anaerobic digestion and effect of pH and Eh," J Soutwest Jiaotong University, China (2001).
[11] Poljun P, "Biogas technology handbook Thailand," Office of technology transfer and dissemination department of energy and energy conservation, Thailand (2014).
[12] Yadvika, Santosh, Srakrishnan TR, Sangeeta K and Vineet R, "Enhancement of biogas production from solid substrates using different techniques–a review," Bioresource Technol, 95 (2004) 1–10.
[13] James LW, "Handbook on biogas utilization," Georgia institute of Technology, Georgia (1998).
[14] Mital K, "Biogas systems–Principles and Applications New International (P) Ltd, New Delhi, India (1996).
[15] Teodorita AS, Dominik R, Heinz P, Michael K, Tobias F, Silke and Rainer J, "Biogas handbook," University of Southern Denmark Esbjerg, Denmark (2008).
[16] Su Y, Tian R, and Yang XH, "Research and analysis of solar heating biogas fermentation system," Procedia Environmental Sciences, 11 (2011) 1386–1391.
[17] Bansal NK, "A study of a greenhouse concept on conventional biogas systems for enhancing biogas yield in winter montio," Energy Resources, 9 (1985) 119–128.
[18] Zhiguang C and Chaokui Q, "Experimental and simulation of a solar–assisted household biogas system," Energy procedia, 61 (2014) 1760–1763.
[19] Desai CK; 1987; Use of solar pond for thermal control of biogas plant; Proceeding of the International seminar on solar energy and rural development; Kolhapur Shivaji University; India.
[20] Fehqing D, Jianbo L, "Using solar energy to enhance biogas production from livestock residue–A case study of the Tongren biogas engineering pig farm in South China," Energy, 57 (2013) 759–765.