

Article

Effects of Seasonal Temperature Variation on Slurry Temperature and Biogas Composition of a Commercial Fixed-Dome Anaerobic Digester Used in Bangladesh

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Abstract: Biogas is produced in Bangladesh mostly through fixed-dome anaerobic digesters, which usually operate without any temperature controller. An experiment was conducted to monitor the seasonal temperature variation inside a fixed-dome type digester and its effect on biogas composition. A commercial-scale digester with a working volume of 350 m³ was used for this study. Three k-type thermocouple sensors were used to monitor the ambient, biogas, and slurry temperatures in real-time. The results showed that the average ambient temperature in the autumn, late autumn, and winter was 29.05, 22.90, and 17.64 °C, respectively. The average slurry temperature in the autumn (30.38 °C) was higher than in the late autumn (29.36 °C) and in the winter (25.76 °C). The highest and lowest slurry temperatures were found to be 31.11 and 24.47 °C, respectively, which indicated that the digester worked within a wide temperature range, establishing both psychrophilic and mesophilic operational conditions. Higher methane concentrations were observed in the autumn than in the late autumn and winter. The CO₂ and H₂S concentrations were higher in the winter than those of in the autumn and late autumn. The electricity generation in the winter was 47.85% and 45.15% lower than in the autumn and late autumn, respectively.

Keywords: anaerobic digestion; fixed-dome digester; temperature; seasonal variation; biogas



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1. Introduction

Bangladesh is a densely populated country with a population of around 170 million [1]. Per capita electricity consumption in the country is 375 kWh per year [2], which is the lowest among the South Asian countries, with corresponding consumption in India of 970 kWh, Sri Lanka of 650 kWh, and Pakistan of 590 kWh, respectively [3]. The energy generation in Bangladesh mostly depends on fossil fuels (where natural gas is the main source) with a mere share of 1.61% from renewable sources [4]. As of today, the country has a limited natural gas reserve (i.e., 12 trillion cubic feet till to date) which may run only for the next 10–12 years [5]. Due to rapid industrialization and continuous population growth, the countrywide demand for energy is rising swiftly, causing a tremendous pressure on the present natural gas demand. As a result, there has been an ongoing search for suitable alternative energy sources for power generation with a potential for greenhouse gas mitigation. Biogas seems to be a promising alternative in this context, as it is produced from renewable sources, often from organic waste materials, which has low or no impact towards greenhouse gas emissions, once utilized for energy production.

Biogas is produced through anaerobic digestion (AD) by the action of microorganisms in an anoxic environment. There are several factors which influence the performance of

AD. Digester temperature is one of the vital factors which influences microbial activity and growth. The AD typically takes place in three distinct temperature regions: psychrophilic (<30 °C), mesophilic (30–40 °C), and thermophilic (50–60 °C) [6]. The methanogens are mainly effective in mesophilic and thermophilic regions where AD shows higher productivity. Previous studies on the effect of temperature on anaerobic digestion found higher methane yield in the mesophilic temperature range as compared to thermophilic condition [7,8]. Generally, a temperature range of 35–37 °C is suggested optimum for methane production in mesophilic conditions [9]. However, at a lower temperature range, such as at 22–28 °C, methane production tends to be 23–30% lower than that at 35 °C [6,10]. Schmidt et al. [11] found that fluctuations in temperature reduce the biogas productivity of AD. Barik and Murugan [12] observed that methanogens are very sensitive to speedy changes in temperature with any drastic change resulting in process failure, which is thus recommended to be avoided by implementing correct measures. The correlation between the reaction rate and the biological process with temperature can be shown by Equation (1) [7]:

$$r_T = r_{20}\theta^{(T-20)} \quad (1)$$

where r_T represents the reaction rate constant at temperature T , r_{20} denotes the reaction rate constant at 20 °C, θ represents the temperature activity constant, and T is the temperature.

Poultry is one of the major livestock sectors in Bangladesh [13]. The poultry population of the country is around 312 million, which produces around 2.1 MTPY (million tons per year) of waste (dry matter) with a corresponding production of 12.3 MTPY from cattle, 0.7 MTPY from buffalo, 1.5 MTPY from goats, and 0.2 MTPY from sheep, respectively [14]. There are around 20,000 farms having 1000 or more birds, which have a considerable potential to generate electricity using the produced waste [15]. Talukder [15] showed that the poultry litter had an electricity generation potential of 490 GWh out of the total electricity generation of about 26,604 GWh in the year 2009. In recent development, the poultry population is increasing at a much higher rate than other livestock due to the increased consumption of poultry meat. As the poultry industry grows continuously, it contributes to generate a significant portion of the waste generated from the entire livestock sector. Thus, a systematic waste management strategy to utilize this waste in an environmentally friendly way is urgently needed.

In Bangladesh, there are around 91,350 domestic and commercial biogas plants in operation [16]. Most of the plants are single substrate (cattle or poultry manure)-based and use a fixed-dome type digester. These plants are operating without any heating system for temperature control, and their performance among other things depends heavily on ambient temperature [17]. Bangladesh has a sub-tropical monsoon climate containing four major seasons: winter, spring, summer, and autumn [18]. It has a wide seasonal variation in rainfall, with moderately warm temperatures and high humidity [19]. The average temperature from April to August is about 30 °C [20], which is around optimum for biogas production [21]. However, the temperature starts to fall from September till February (winter) [20]. In the winter, the mean temperature is around 18 °C, which sometimes drops below 10 °C due to cold waves [19]. The low temperatures in the winter season may influence the performance of AD. Thus far, most of the previous studies [7,8] on the effect of temperature on AD performance were conducted at a laboratory scale, with studies on commercial-scale digesters being extremely rare. In addition, little information is available on how changes in ambient temperature influence the process temperature of a full-scale anaerobic digester. Kalia et al. [22] evaluated the performance of a fixed-dome digester in India under seasonal temperature variations. They found that a fall in the mean ambient temperature from ca. 26 °C in the summer to ca. 9 °C in the winter months resulted in a drop in the digester temperature from ca. 22 to 13 °C. Ihara et al. [23] observed improvement in biogas production with an increase in ambient temperature in a field-scale digester in Japan. Castano et al. [24] evaluated the performance of a small-scale fixed-dome digester in a temperate U.S. climate for 363 days. They observed that the digester temperature below 20 °C produced less biogas than expected. Besides these studies, the knowledge of

seasonal temperature effect on commercial-scale digesters in Bangladesh context to date is insufficient. Moreover, studies devoted to poultry manure as a feedstock are even scarcer, with very few previous studies [22,24] reporting the performance of digesters treating cattle manure only. To address this research gap, the aim of the current work was to investigate the effect of seasonal temperature variations on the digester temperature and biogas quality by using a fixed-dome biogas digester treating local poultry litter in Bangladesh conditions.

2. Materials and Methods

2.1. Experimental Site and Biogas Plant

The experiment was conducted in a poultry farm situated in Gazipur, Bangladesh (GPS coordinates 24°9'41.32" N, 90°25'10.74" E) (Figure 1). An overview of the farm is presented in Table 1. The farm has 60,000 birds, which produce ca. 12,000 kg of poultry litter per day. The farm is covered by a poultry shed, which is a standard accommodation environment for birds with proper aeration, shelter, safety, and drainage systems. In order to treat the poultry litter for biogas production for electricity generation, the farm uses a fixed-dome type digester of 350 m³, which is made of bricks and constructed underground. The generated poultry litter within the farm is collected using a belt conveyor. After collection, the poultry litter is flushed with water at room temperature to enable feeding into the digester through the inlet. The room temperature and humidity are maintained by a pad and fan cooling system in the summer and by lighting and closing curtains in the winter, respectively. Residue of the digestion, called digestate, is brought out from the digester through the outlet to prevent the increase in biogas exit pressure.

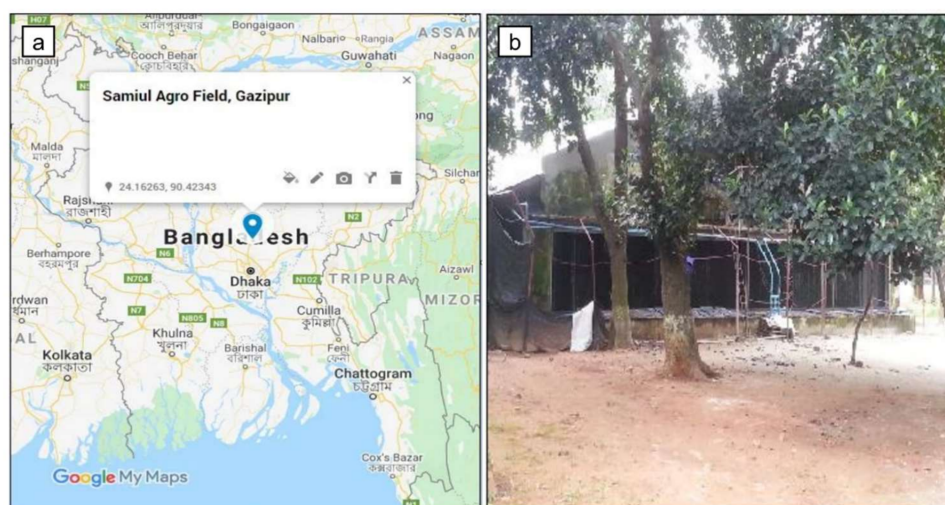


Figure 1. (a) Location of the study site; (b) picture of the farm.

Table 1. An overview of the farm.

Parameter	Value
Capacity of the digester (m ³)	350
Digester type	Fixed dome
Feedstock	Poultry droppings
Population (no. of birds)	60,000
Waste produced (kg/d)	12,000
Waste fed into the digester (kg/d)	3000

2.2. Experiment Period

Considering the seasonal temperature variation of Bangladesh as stated in the introduction, the experiment was conducted in the autumn, late autumn, and winter seasons, starting from 24 August 2017 till 10 February 2018. Autumn spans from mid-August

to mid-October, late autumn is from mid-October to mid-December, and winter is from mid-December to mid-February.

2.3. Experimental Set-Up and Procedure

For the experiment, a set-up was prepared in a control room where a computer (15-BA009DX, HP, USA) and a data logger (CR6, Campbell Scientific Inc., Logan, UT, USA) were placed (Figure 2). The room was facilitated with continuous electricity supply to ensure continuous operation of the computer and the data logger. Temperature at different locations was recorded by the data logger through three different k-type thermocouples (Temperature 107 probe, Campbell Scientific Inc., Logan, UT, USA). Two thermocouples were placed inside the digester at the gas outlet for measuring the biogas temperature and slurry temperature at a depth of 0.91 m and 2.13 m, respectively, and the other sensor was exposed into the atmosphere for the measurement of ambient temperature (Figure 2). The data logger saved data every minute of the interval, which eventually allowed to process data for every hour and every three hours for display. It was assumed that no temperature gradient exists inside the digester at any depth. Therefore, the single point measurement of the slurry temperature represents the temperature of all points. This assumption is supported by Terradas-III et al. [25], who observed no significant change in slurry temperature with the depth of the digester, namely, 24.80 °C at 1 m, 24.50 °C at 1.4 m, and 24.40 °C at 1.8 m depth, respectively.

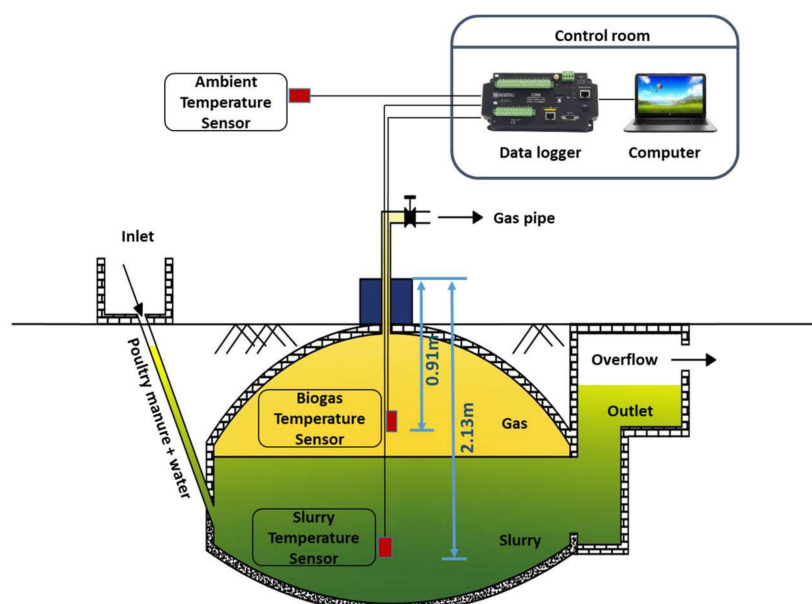


Figure 2. Fixed-dome digester with experimental set-up.

2.4. Measurement of Different Parameters

During the experiment, the feedstock and slurry samples were collected for laboratory analysis. The collected samples were brought to the Green Energy Knowledge Hub (GEKH) laboratory at Bangladesh Agricultural University (BAU) for physical and chemical analyses. The total solids (TS) and volatile solids (VS) were determined using the following standard [26], as described by Nasrin et al. [27]. For drying and combustion of samples for TS and VS evaluation, a heating oven (UN30, Memmert, Schwabach, Germany) and a muffle furnace (LE 14/11/ B 150, Nabertherm, Lilienthal, Germany) were used. The pH of the samples was measured by a calibrated pH/Conductometer (914 pH/Conductometer, Metrohm, Herisau, Switzerland). The biogas composition (CH_4 , CO_2 , and H_2S) was measured at an interval of around 20 days using a biogas analyzer (Biogas 5000, Geotech Ltd., Coventry, UK). Biogas volume could not be measured due to the unavailability of a

biogas volume measuring system for the field-scale fixed-dome digester. Instead, the data on daily electricity production (kWh/day) from biogas was obtained from the farm owner.

2.5. Statistical Analysis

Statistical analysis was performed upon data collection. Significant statistical difference was determined using IBM SPSS Statistics 20 software. Multiple comparison tests were conducted using Tukey's HSD (honestly significant difference) test method.

3. Results and Discussion

3.1. Substrate and Slurry Characteristics

The substrate and slurry characteristics are presented in Table 2. The TS and VS contents of the substrate were in the range of 6% to 17% and 4% to 11%, respectively. The dry matter content of the input feedstock was found to vary from time to time due to the non-uniform mixing of the poultry litter and water, as the plant owner did not have enough resources for monitoring and controlling the feedstock input at the point of feeding.

Table 2. Substrate and slurry characteristics.

Date	Substrate			Slurry		
	TS (%)	VS (%)	pH	TS (%)	VS (%)	pH
24-08-17	17.08	10.78	5.95	1.02	0.44	7.09
14-09-17	6.45	4.26	6.27	0.83	0.33	7.63
09-10-17	10.54	6.65	7.65	1.29	0.52	8.04
01-11-17	6.25	4.18	7.46	1.25	0.51	7.95
14-12-17	6.5	4.12	6.39	1.15	0.46	6.96
04-01-18	10.16	6.63	6.54	1.13	0.47	6.83
10-02-18	10.27	6.88	6.82	3.03	1.24	5.96

The pH is known to influence enzymatic activity associated with different AD processing steps. Each enzyme is active within only a specific and narrow pH range and presents its maximum activity at an optimum pH. The pH value and the stability of the pH in an anaerobic digester are extremely important to maintain a high rate of methanogenesis, which develops when pH is kept within a neutral range [28]. The AD is stabilized at a pH of 6.5 to 8.2 [29]. In this study, the pH value of the digester slurry was higher in the autumn than in the late autumn and winter (Table 2). Similar results were obtained by the previous studies [7,8], which observed low pH levels at low slurry temperatures.

As for TS and VS contents of the digestate, the amounts as compared to those of the input substrate were found to be much less (Table 2). This represents that a significant portion of the VS in the input substrate was involved in the biochemical conversion and therefore turned into biogas.

3.2. Seasonal and Diurnal Temperature Variation

The seasonal variation of the ambient temperature and the corresponding slurry and biogas temperature are shown in Figure 3. From the figure, it is evident that the average biogas and slurry temperature decreased with the decrease in average ambient temperature. During the experiment, the maximum ambient temperature was found to be 41.31 °C on September 23 and the minimum ambient temperature of 5.08 °C on January 8. Correspondingly, the maximum and minimum biogas temperatures were 32.63 and 16.83 °C recorded on August 25 and December 4, respectively, while the maximum and minimum recorded slurry temperatures were 31.11 and 24.47 °C on September 19 and January 16, respectively. The variable slurry temperature throughout the different seasons suggests that the digester established both psychrophilic and mesophilic conditions during its operation.

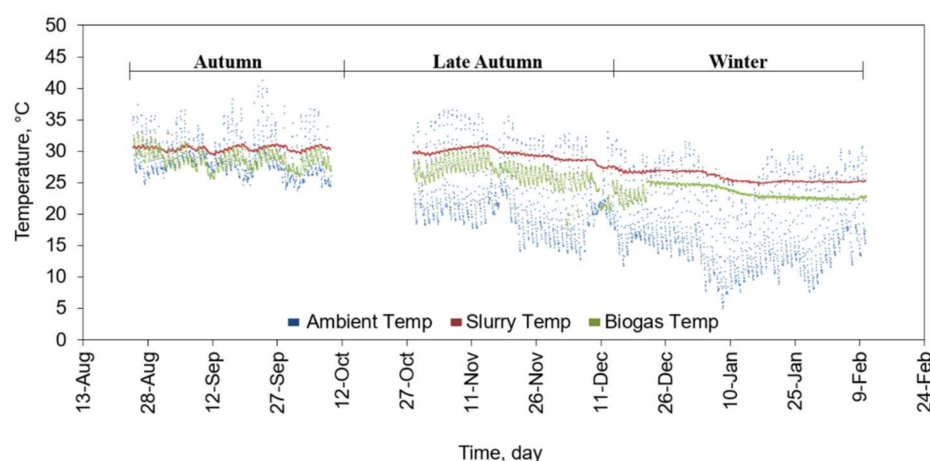


Figure 3. Variation of ambient, biogas, and slurry temperature over the experimental period.

The average ambient temperature in the autumn, late autumn, and winter was 29.05 ± 3.07 °C, 22.90 ± 5.47 °C, and 17.64 ± 6 °C, respectively. Due to technical difficulty of the data logger, data from October 10 to October 27 could not be registered. The ambient temperature in the autumn was 6.15 °C higher than that in the late autumn and 11.41 °C higher than that in the winter. The results of an ANOVA test showed that the ambient temperature in the autumn was significantly higher than that in the late autumn and winter ($p < 0.05$), respectively (Table 3).

Table 3. Changes in the ambient temperature and slurry temperature.

Name of the Season	Ambient Temperature (°C) (Mean \pm SD)	Slurry Temperature (°C) (Mean \pm SD)
Autumn	29.05 ± 3.07 ^a	30.38 ± 0.38 ^a
Late autumn	22.90 ± 5.47 ^b	29.36 ± 0.96 ^a
Winter	17.64 ± 6 ^c	25.76 ± 0.78 ^b

^{a-c} Within each column, different letters indicate a significantly increased difference ($p < 0.05$).

The immediate change in the slurry temperature after feeding the digester was monitored and shown in Figure 4. The digester was fed with influent (mixture of poultry litter and water) once daily between 11.00 AM and 12.00 PM throughout the experiment. As shown, the slurry temperature remains unaffected by the addition of the influent.

In the autumn, the maximum ambient and biogas temperature fluctuations were found to be 4.01 °C (1:00 PM) and 1.29 °C (7:00 PM), respectively (Figure 5). The fluctuation in slurry temperature was very low during the autumn, which is desirable for a stable AD operation. The average slurry temperature during the autumn was found to be 30.38 ± 0.38 °C. The variation of the ambient temperature between day and night was around 2.94 ± 1.41 °C.

In the late autumn, the recorded maximum ambient and biogas temperature fluctuations were 3.44 °C (1:00 PM) and 1.19 °C (7:00 PM), respectively (Figure 6). The fluctuation in slurry temperature was not significant. The average slurry temperature in the late autumn was 29.36 ± 0.96 °C, which was 1.02 °C lower than autumn's slurry temperature. During the night, the ambient temperature dropped by 7.54 ± 2.14 °C, which although is significant, did not affect the slurry temperature.

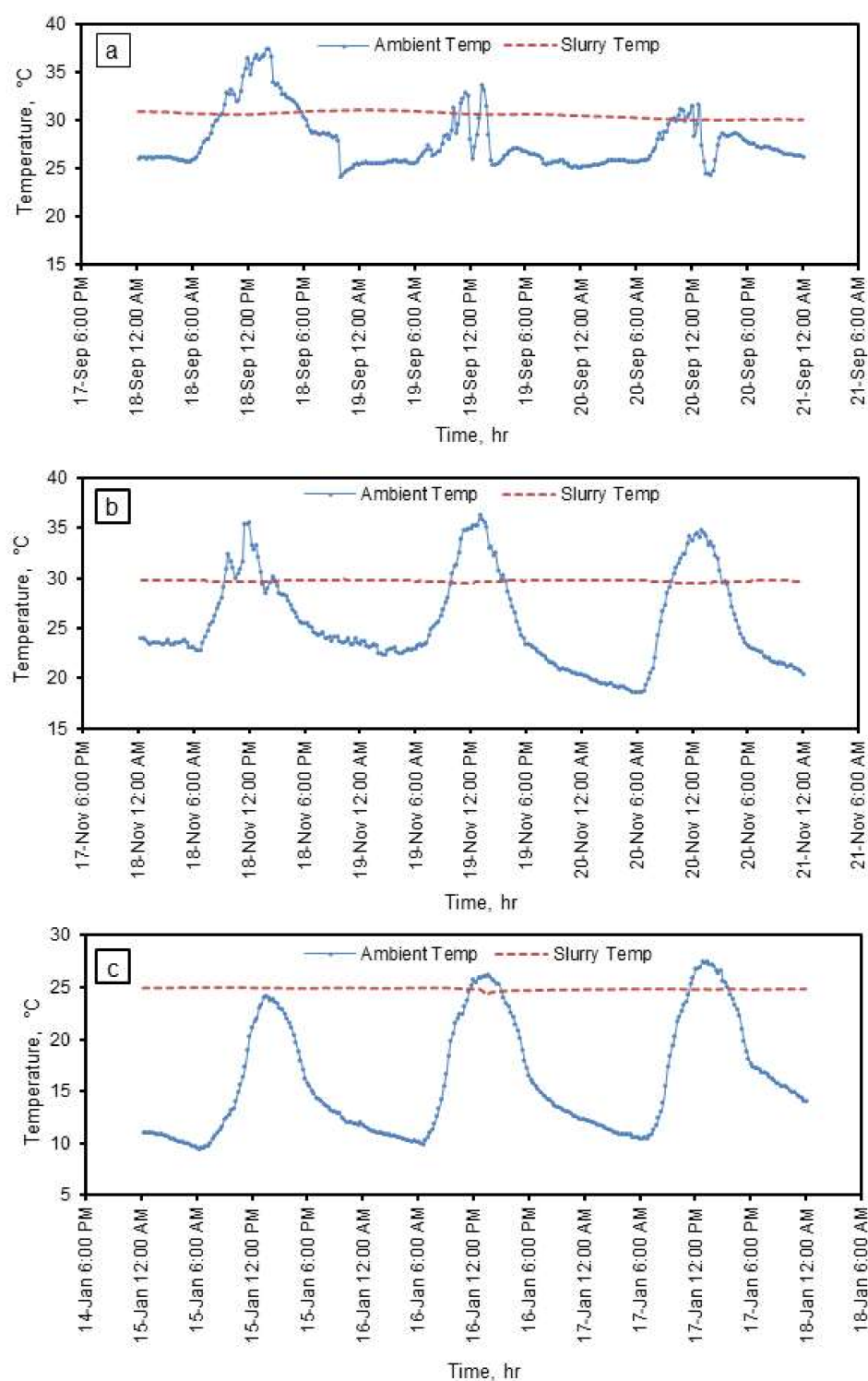


Figure 4. Changes in slurry temperature after feeding in (a) autumn (18 to 21 September 2017), (b) late autumn (18 to 21 November 2017), and (c) winter (15 to 18 January 2018).

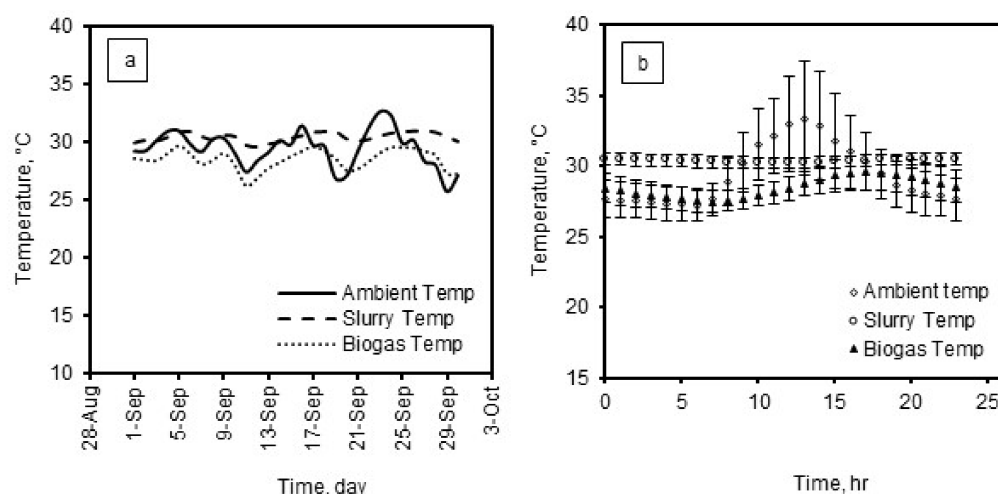


Figure 5. (a) Daily and (b) diel ambient, biogas, and slurry temperature variations in the autumn season.

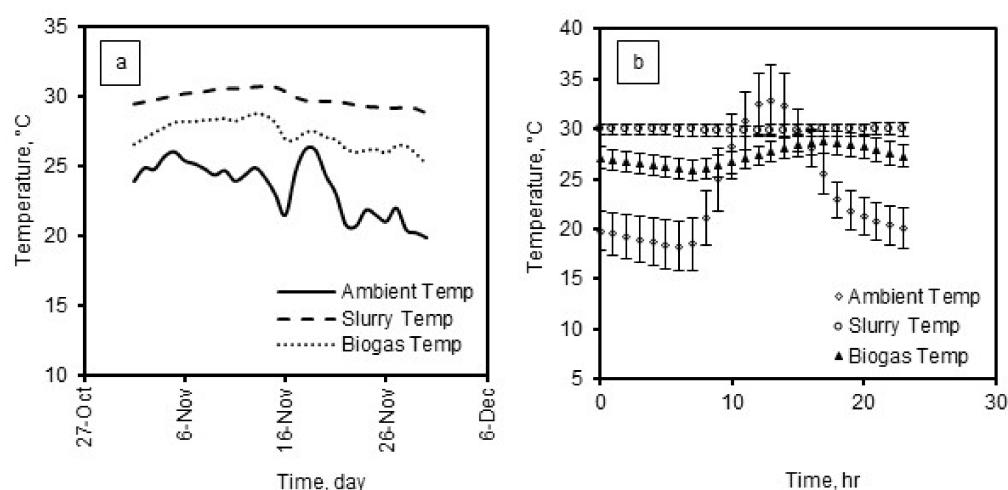


Figure 6. (a) Daily and (b) diel ambient, biogas, and slurry temperature variations in the late autumn season.

The maximum ambient temperature fluctuation in the winter was found to be $4.94\text{ }^{\circ}\text{C}$ (11:00 AM). The average ambient temperature at 11:00 AM was $21.63\text{ }^{\circ}\text{C}$. No significant fluctuation in the slurry temperature was observed in the winter months (Figure 7), but the average slurry temperature in the winter dropped to $25.76 \pm 0.78\text{ }^{\circ}\text{C}$, which was 5.64 and $4.62\text{ }^{\circ}\text{C}$ lower than that in the autumn and late autumn, respectively. The ambient temperature at night fell by $8.69 \pm 2.12\text{ }^{\circ}\text{C}$. This drop in temperature during the night was higher than the above two seasons.

The results of this study showed that during a specific season, the variation of slurry temperature was not related to the variation in ambient temperature, which coincides with the findings of the previous study by Kalia et al. [30]. However, in the long run, the average slurry temperature decreased gradually from the autumn to winter. There was no significant difference in slurry temperature between the autumn and late autumn, but the temperature was significantly lower in the winter ($p < 0.05$). The slurry temperature dropped as the average ambient temperature fell gradually from the late autumn to winter. Similarly, the average biogas temperature also decreased with the drop in average ambient temperature in these periods of the year. Thus, it can be said that the ambient temperature is directly proportional to the biogas and slurry temperature; hence, it may influence the AD performance.

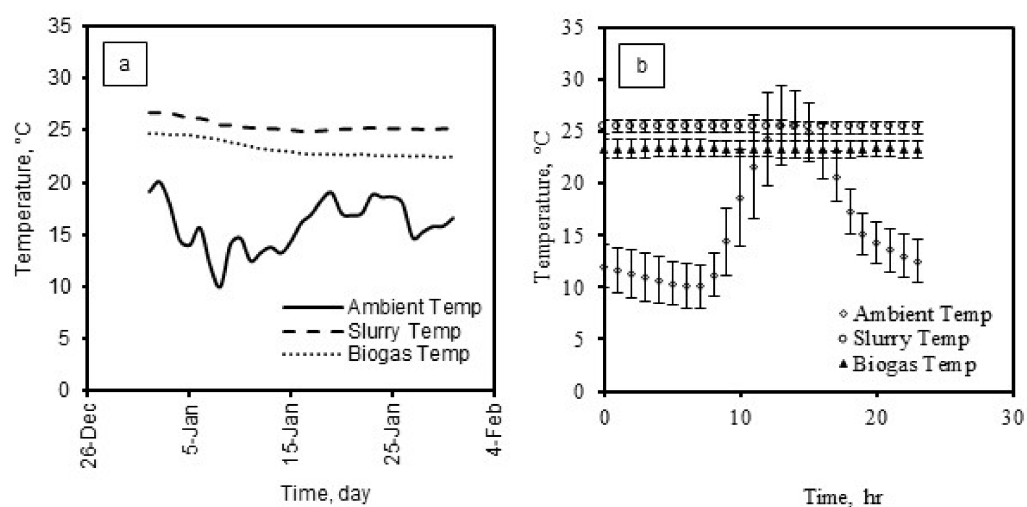


Figure 7. (a) Daily and (b) diel ambient, biogas, and slurry temperature variations in the winter season.

3.3. Effect on Degradation Efficiency

Total solids reduction (TSR) and volatile solids reduction (VSR) are two important measures of AD degradation efficiency. In this study, the TSR in the autumn, late autumn, and winter was found to be 89.64%, 81.15%, and 79.68%, respectively, and the VSR was 93.45%, 88.31%, and 87.44%, respectively (Figure 8). It is evident from the results that the degradation efficiency decreased from the autumn to winter as the digester temperature declined from 30.38 to 25.76 °C. During AD, microorganisms break down waste materials into sugars and fatty acids. Fatty acids are then converted into biogas by the action of methane forming bacteria and archaea. This process causes a reduction of solid particles in the organic materials. At low temperature, the metabolic activity of microorganisms decreases, resulting in lower degradation efficiency [31]. Nandi et al. [7] observed low degradation efficiency at lower temperatures than that of higher temperatures. The study obtained the volatile solids degradation of 29–33% between 35 and 40 °C, and of 12–19% between 20 and 25 °C. A digester temperature higher than 40 °C resulted in lower degradation efficiency. The study concluded that an optimum temperature should be maintained to achieve a higher degradation of organic matter.

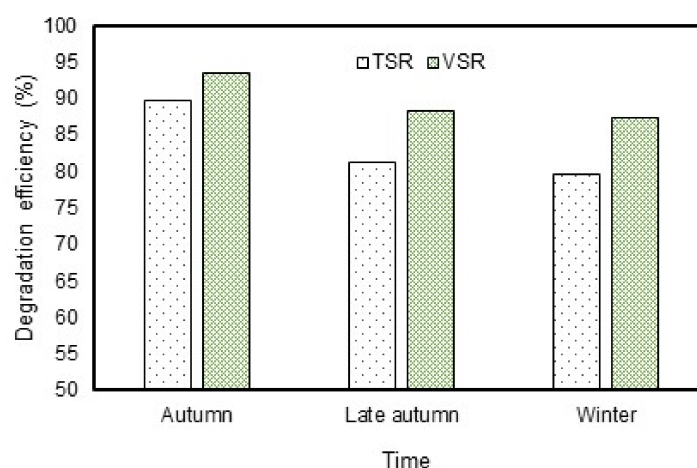


Figure 8. Variation of degradation efficiency.

3.4. Seasonal Variation of Gas Composition

According to a number of researchers [32,33], the variations in CH₄ production and emissions from biogas plants have been correlated to the slurry temperature. In this study, the slurry temperature in the autumn was higher than that in the winter. The

seasonal variation of gas composition is shown in Figure 9. It is evident that the methane concentration decreased with the decrease in average temperature from autumn to winter (Figure 9a). The average methane concentration was 61.43%, 59.75%, and 56.3% in the autumn, late autumn, and winter, respectively. Thus, the methane concentration in winter was 8.35% and 5.77% less than the methane concentration in the autumn and late autumn, respectively. This observation suggests that the methane production decreases with the decrease in temperature. Similar results were obtained in the study by Vanegas and Bartlett [34], who found lower methane concentration at 20 °C (45%) than at 35 °C (62%). An increase in temperature leads to increased bacterial activity with higher growth rates, faster metabolism, and elevated nutrient demand. If the temperature falls below the optimum range, bacterial metabolism decreases. As a result, methane concentration in biogas decreases or completely disappears with the proportional increase of CO₂ level [7]. However, results of the ANOVA test showed that the difference in methane concentration in different seasons was not significant ($p = 0.10$).

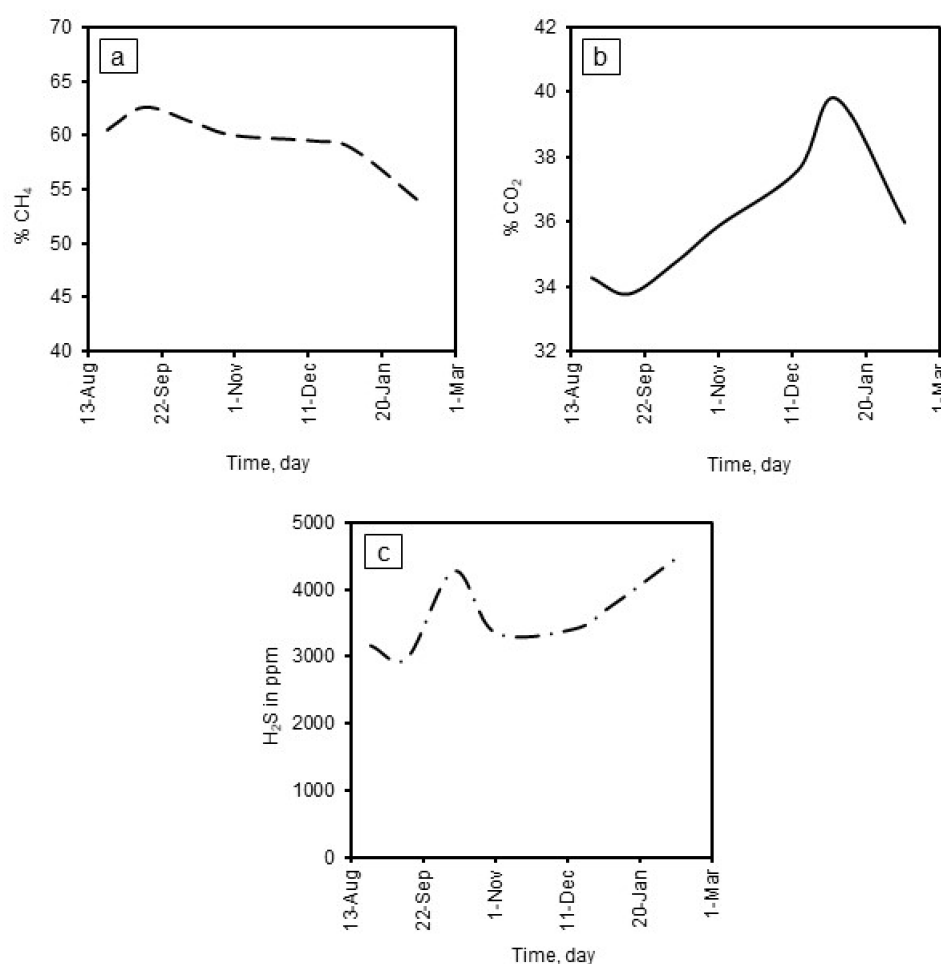


Figure 9. Seasonal variation of biogas composition: (a) CH₄; (b) CO₂; and (c) H₂S.

Apart from AD temperature, the CH₄ concentration in biogas also depends on the pH, as it affects the speciation of the carbonate system and the release of CO₂ [7]. The biogas composition shifts more toward CH₄ when the pH is high due to increased alkalinity caused by NH₃ release. In this study, the pH in the autumn was higher and stable than that in the late autumn and winter. Nandi et al. [7] reported a stable and neutral pH at higher temperatures (30 and 35 °C) than at low temperatures (20 and 25 °C), which resulted in higher CH₄ concentration. From the autumn to winter, the CH₄ concentration decreased with a corresponding rise in CO₂ concentration due to the drop in pH (Figure 9b).

The H_2S is considered as an impurity in the biogas composition. Biogas can be used to fuel combustion engines. High amounts of H_2S in biogas can be corrosive to the engine and metal parts through the emission of SO_2 during combustion, especially when the engine is not operated continuously. Furthermore, combustible products of H_2S -laden biogas may contain toxic $\text{H}_2\text{S}/\text{SO}_2$ gas mixture which is detrimental to human health at the occupational level [35]. Besides the downstream impact, high concentration of H_2S can affect the AD process itself, resulting in collapse or even failure of it in worst cases [36]. In the present context, the average H_2S concentration in the winter was 4128 ppm, which was higher than that of in the autumn (3470 ppm) and late autumn (3379.5 ppm), respectively (Figure 9c). The highest H_2S concentration was measured as 4499 ppm on February 10, which represents the middle of winter. Jung et al. [37] also observed high H_2S concentration at low ambient temperature. It was interesting to see that the H_2S concentration obtained in this experiment was much higher than in the laboratory experiments conducted by Saha et al. [38], who obtained a H_2S concentration of 225 ppm. The difference was perhaps due to the different mode of operation or operating conditions [39]. The lab-scale study [38] was conducted using batch bottles in a controlled environment. The batch digester was filled with substrates and then sealed till the end of the experiment, whereas the present study was conducted using a fixed-dome digester of continuous mode in an uncontrolled environment. Haghighatafshar [40] observed a high growth rate of sulfate-reducing bacteria in continuous digestion, which resulted in high concentration of H_2S in biogas. A high concentration of H_2S in the field-scale digester was also observed in a previous study [41], which observed an average H_2S concentration of 4310 ppm from an anaerobic digester treating dairy manure. The H_2S in biogas comes from inorganic sulfate that presents in the feedstock. The H_2S is produced through the action of sulfate-reducing bacteria which compete with methanogens for the intermediate carbon sources [42]. High H_2S concentration in the winter season might be due to higher activity of sulfate-reducing bacteria than methanogens causing a high rate of sulfidogenesis [43]. Thus, it can be concluded that the low temperature is responsible for higher H_2S concentration during the winter season. The presence of H_2S hinders the production of methane [44], making biogas unsuitable for downstream application. As for example, the recommended concentration of H_2S in biogas is <10 ppm for kitchen stoves, <500 ppm for combustion engines, and <1000 ppm for boilers, respectively [45], suggesting that the filtering of biogas is necessary before feeding to an engine or to other biogas-run applications.

3.5. Electricity Production

Figure 10 shows the average daily electricity production from the produced biogas in different seasons. The results show that electricity production in the winter (182.5 kWh) was 47.85% and 45.15% lower than in the autumn (350 kWh) and late autumn (332.72 kWh), respectively. However, electricity production in the late autumn was only 4.94% lower than in the autumn. With the produced biogas, a generator of 100 kW could run for 3.5, 3.33, and 1.83 h in the autumn, late autumn, and winter months, respectively. The reason for less electricity production in the winter can be correlated with the lower digester temperature (25.76 °C), which might have influenced the biogas production and consequently lowered the methane concentration in the biogas by compromising the metabolic activity of methane formers.

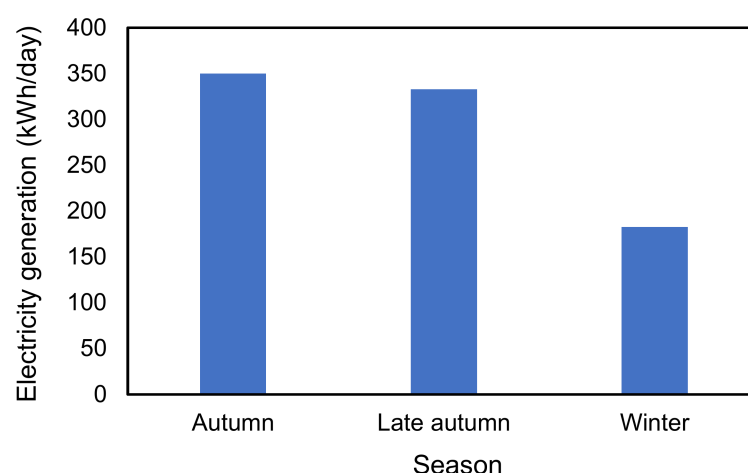


Figure 10. Daily average electricity generation in different seasons.

3.6. Digester Heating

Based on the present investigation, it seems that the digester should use a heating unit for temperature control as the digester temperature was found to often deviate to some extent from the optimum AD temperature. Installing such a unit is also likely to improve AD performance in terms of maximizing biogas yield with minimum H_2S production. However, digester heating could result in extra costs for biogas plant operation. A number of previous studies examined the various ways of reducing the cost of digester heating, employing waste heat, solar heating, or surplus heat using heat pumps or heat exchangers [46]. For example, Liu et al. [47] evaluated the performance of a groundwater source heat pump to heat the digester in the winter and found a saving of 44% standard coal consumption. Gaballah et al. [48] developed a greenhouse-assisted solar heating system, where the greenhouse was made with polyethylene plastic. The study concluded that a digester temperature of around 5 °C higher than the ambient temperature can be reached using the proposed system. Dong and Lu [49] proposed a solar heating system, in which water is heated first by a solar collector, and then directly added to the digester. The system showed 11.3% improvement in the biogas yield over the unheated digester. Axaopoulos [50] proposed a solar heating system for an underground digester. The digester was constructed with flat plate solar collectors with an area of 32 m². The results showed that by using the heating system, the digester temperature could be maintained at about 33.5 °C. However, a combined heat and power generation (CHP) system would be most appropriate for a commercial-scale plant as they intend to produce both heat and electricity. The waste heat from the combustion of biogas can be utilized to heat the digester content by using heating pipes (internal heating) or to preheat the substrate prior to feeding into the digester using a heat exchanger (external heating) [51]. Lantz [52] found a drastic reduction in the cost of biogas production using a CHP system with a compression ignition engine, where heat exchangers were used to heat the substrate to maintain the optimum digester temperature.

In line with the above studies, design and installation of a digester heating unit suitable with regard to both AD performance and cost remains to be a scope of the future research based on the current work.

4. Conclusions

The operational temperature and performance of a fixed-dome type digester at local conditions were monitored. The result showed that during a specific season the slurry temperature remained nearly constant, but in the long run the slurry temperature decreased from autumn to winter due to the drop in ambient temperature. The biogas composition varied seasonally as a result of temperature variations from season to season. Higher methane and lower CO_2 concentrations were observed in the autumn than in the late au-

tumn and winter. The H₂S concentration was higher during the winter than in the autumn and late autumn seasons. The electricity generation from produced biogas was much lower in the winter than in the autumn and late autumn. Since the drop in temperature from the autumn to winter resulted in reduced methane concentration and higher H₂S production, it is recommended to use a heating control unit in the winter season to avoid instability in biogas production. Additionally, before using the biogas to generate electricity via combustion, the H₂S cleaning unit prior to biogas feeding to the system should be added.

As the experiment was conducted for six months, further study could be carried out considering all year-round temperature variations. In addition, an economic analysis of the digester with a heating unit can be performed to understand the economic viability of the system.

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