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Methane Production from Food Garbage under the Batch and Semi-Continuous Anaerobic Digestion: Effect of Total Solid

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ABSTRACT

In line with modern era, it is a high demand of renewable energies due to fossil fuels crisis. This study applies food garbage to produce biogas - an alternative renewable energy source – under lab-scale batch and semi-continuous reactors. Designing with four loading total solid (TS) rates of 1.0%, 1.5%, 2.0%, and 2.5%, the batch and the semi-continuous testing set up in 1.5 L and 21 L plastic reactors, respectively. Both testing was run in 60 days, produced biogas volume and compositions were recorded daily in semi-continuous reactors, and every ten days in the batch reactors. The results show that in batch testing, the biogas yields of treatments 1.0%TS, 1.5%TS, and 2.0%TS were better than those for treatment of 2.5%TS; however, $\%CH_4$ concentrations were better for treatments 2.0%TS and 2.5%TS. For the semi-continuous testing, the loading rate of 2.5% total solid food garbage produced the highest biogas yield which could meet the household demand of daily gas. Up to the day of 60, the $\%CH_4$ concentration was nearly 45% which proof the biogas can be used for cooking. H_2S concentration in biogas was high which must be reduced to use produced biogas for cooking purpose. Further study needs to avoid accumulation of *soluble* organic acids, leading the low pH and inhibits methane-producing microorganisms in food garbage anaerobic reactor.

Keywords: batch digester, biogas, food garbage, semi-continuous digester, total solid.

INTRODUCTION

Nowadays, the increase in population leads to a rise in energy demand (Gray, 2017). The point is that the current energy system still strongly depends on fossil fuels which significantly causes the increasing level of greenhouse gases and leads to other environmental problems (Rahman and Vu, 2021). Furthermore, there is a problem with the deficiency of access to modern energy, in which approximately 20% of the global population lacks access to electricity (Roser, 2020). Therefore, it is ideal that reasonable, sustainable, and reachable modern energy for people while solving environmental problems is an urgent need (Ürge-Vorsatz et al., 2015). The share of energy use from renewable energy is progressing in the direction of decreasing the environmental impact of energy use. Renewable energy sources such as hydrothermal, geothermal, solar, wind, and biogenic energies are generally considered to be friendly to the environment, with very low net emissions of CO_2 per unit of energy produced. Emissions of other pollutants are also regularly lower to the production of renewable energy than for energy production from fossil fuels (Balcioglu et al., 2017).

Biogas is renewable energy and friendly-to-environment fuel, is evolving to substitute partly fossil fuels, then conveys to sustainable development (Vasco-Correa et al., 2018). In Vietnam, biogas system has been applied very successfully in the treatment of livestock garbage and creation of biogas for cooking or electricity generation in rural areas in Vietnam (Noi et al., 2022; Thu at el., 2012), contributing to reduce of greenhouse emission (Izumi et al., 2015). In the other hand, increase in population causes huge disposal of garbage and this disposal causes problems to environment (Abdel-Shafy and Mansour, 2018). Food garbage accounts of high percentage in domestic garbage, is used to produce composts commonly; however, not all households having conditions to produce composts. Thus, an approach of food garbage by producing energy is concerned (Pathak et al., 2022). In rural Vietnam, the rate of garbage collection, including food garbage, is quite low (65.7%). In addition, the food garbage component accounts for a high proportion (50-70%). Additionally, there is not yet an official system of garbage separation in the Vietnamese rural areas (Ministry of Natural Resources and Environment, 2020). Therefore, research on separation and reuse of food garbage in rural is necessary.

Biogas production from food garbage is a way to reuse food garbage, however, research on biogas production from food garbage or kitchen garbage is quite limited (Pathak et al., 2022). Almost research focuses on aspects of improvement of conditions about the incubated designation, factors of material, and environmental parameters for biogas production from food garbage or kitchen garbage (Zamanzadeh et al., 2017; Vongvichiankul et al., 2017, Satyam et al., 2021). Up to now, there is no information on the study about biogas production from food garbage in consideration of the demand for biogas use by households in rural areas, especially in Vietnam. The low amount of food garbage disposed of in every household in Vietnamese rural areas is very low of 0,11 kg/person/day (Thuan and Thanh, 2022), and the question is how much loading food garbage into fermenting digester to produce adequate biogas for use by households is necessary to figure out. Therefore, this research was conducted to (i) identify loading food garbage ratios that have high biogas production under experimental conditions of the batch anaerobic digester, and (ii) evaluate the aspect of the yield of biogas production for applying practically at households under experimental condition of semi-continuous anaerobic digester. This research contributed to an understanding of the better possibility of the treatment of food garbage and biogas production from food garbage when applied in households or small communities in rural areas in Vietnam.

METHODOLOGIES

Materials

The bio-decomposed food garbage for experiments was collected in a rural place in the Mekong Delta in Vietnam. The component of food garbage included disposed vegetables (43.2% as wet weight), fruit peels and spoiled fruits (39.9%), cooked foods (12.4%), and others (4.5%). The particle size affects biogas generation (Sharma et al., 1988), and the food garbage were shortened to smaller 2 cm to facilitate the faster decomposition process (Thuan and Khanh, 2023; Ngan et al., 2018). They were mixed carefully to have unified samples. Samples of food garbage were analyzed for moisture (%), volatile solids (%VS), total organic carbon (%TOC), and total nitrogen (%TN) before setting up the experiments (Table 1). The inoculum from an anaerobic digester located near the sampling site of kitchen garbage was collected and analyzed for pH = 7.46, alkalinity = 220.6 mg $CaCO_3$/L, ammonium (N-NH_4^+) = 146.2 mg/L, phosphate (P-PO_4^{3-}) = 52.8 mg/L, total solids (TS) = 39.0 mg/L, and VS = 27.5 mg/L. Amendment of inoculum was to accelerate CH_4 production (Ngan et al., 2018).

Experimental designation

The batch anaerobic reactions

The experiments of batch anaerobic reactions followed the general method of Nam et al. (2017). The experiment of batch anaerobic incubation was designed in a plastic bottle with a total volume of 1.5 L. Each reactor contained the fixed inoculum volume of 1.2 L and fed material, and the remaining volume was to contain the generated biogas (0.3 L). The incubation bottle was sealed with a rubber ring placed under the cap, then the bottle was tested for gas leaks. The incubation bottle was directly connected to the gas collection system (a flexible plastic tube with a locking valve was used to collect the generated gas and put it into a vacuumed aluminum bag). There was a plastic tube that was attached to the solution. A syringe of 60 mL was attached to the plastic tube to suck 30 mL of substrate from the plastic

Table 1. Values of moisture, VS, TC, TN and C/N in examined food garbage

Sample	Moisture (%)	VS (%)	TOC (%)	TN (%)	C/N
Food garbage	87.2	5.8	51.3	3.79	13.5

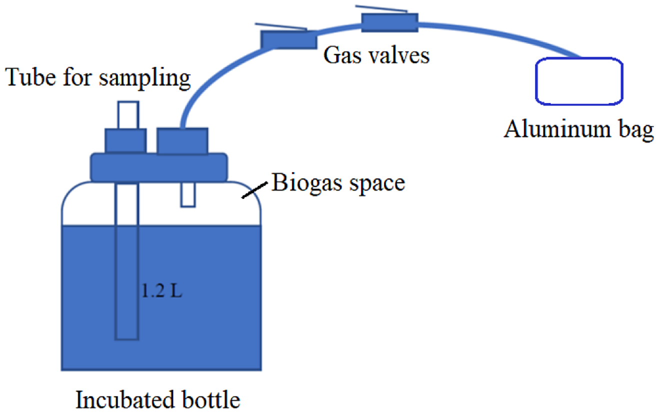

Figure 1. The experimental model of batch anaerobic incubation

Table 2. The loaded TS, VS, and wet weight for each treatment

Treatments	Loaded TS (g)	Loaded VS (g)	Loaded wet weight (g)
1.0%TS	12	3.85	46.84
1.5%TS	18	7.69	93.68
2.0%TS	24	11.54	140.52
2.5%TS	30	15.39	187.35

bottle for measuring control parameters including temperature, pH, and oxidation redox potential (Eh) values. After measurement, substrate was returned into the bottle. After adding materials, gases in the incubation bottles were removed using a vacuum cleaner. Black plastic was used to cover the bottle to prevent sunlight for algae growth (Figure 1).

The experiment was designed to include 4 treatments with different loading TS rates, including 1.0%TS, 1.5%TS, 2.0%TS, and 2.5%TS, and each treatment had three replicates. These loading %TS rates were referred from the research of Nam et al. (2017) for the material of water hyacinth and rice husk. First, an inoculum with a volume of 20 mL was loaded into the incubation bottle, followed by manual loading of the material with the weight corresponding for each prepared treatment to ensure that the material was submerged in the incubator. Then tap water was added to the fixed volume of 1.2 L (Table 2).

The semi-continuous anaerobic reactions

The experiments of semi-continuous anaerobic reactions followed the general method which

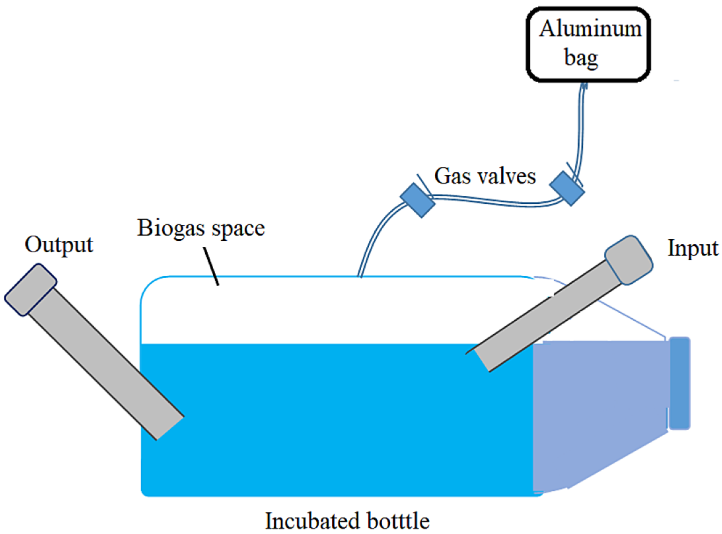

Figure 2. The experimental model of semi-continuous anaerobic incubation

Table 3. The daily loaded materials for each treatment

Treatments	Loaded TS (g)	Loaded VS (g)	Daily loaded wet weight (g)	Total of loaded wet weight for 45 days (g)
1.0%TS	160	121.42	26.55	1194.92
1.5%TS	240	182.13	39.83	1792.38
2.0%TS	320	242.84	53.11	2389.84
2.5%TS	400	303.55	66.38	2987.30

suggested by Thuan and Khanh (2023). The kitchen garbage was incubated in plastic bottles with 21 L (Figure 2). The volume of inoculum and material in the bottles is 16 L and remain volume was space for produced biogas. The incubation bottle is directly connected to the gas collection system as same as the batch anaerobic experiments. The materials were loaded daily through a plastic input tube with φ = 49 mm, and the substrate was sampled for measuring from the input tube. The substrate run out by output tube (φ = 49 mm) (Figure 2).

The experiment was also designed to include four treatments with loading %TS as the batch anaerobic reactors, including 1.0%, 1.5%, 2.0%, and 2.5%; and each treatment had three replicates. First, an inoculum with a volume of 20 mL was loaded into each incubation bottle, followed by manual loading of the material with the weight corresponded for each prepared treatment to ensure that the material was submerged in the incubator. The materials were loaded daily until day 45 of the experiment (Table 3).

Measurement

Both experiments were conducted in the laboratory condition within 60 days. The temperature and pH were measured daily using a portable pH meter (HM-31P, TOA DKK, Japan); whereas oxidation redox potential (ORP) was measured daily using the portable ORP meter of (HM-40P, DKK TOA - Japan). For the first experiment, the volume of produced biogas accumulated in an aluminum bag in every period of 10 days was measured at days of 10, 20, 30, 40, 50, and 60 using a gas volumetric meter (TG 02, Ritter - Germany). For the second experiment, the volume of produced biogas was measured daily. The percentage concentrations of CH_4 and other gases were measured every 10 days and 5 days for the first experiment and the second experiment using a Biogas 5000 gas analyzer (Geotechnology - UK). Additionally, concentrations of hydro sulfur (H_2S) in biogas during the semi-continuous anaerobic experiments were measured using Biogas 5000 gas analyzer (Geotechnology - UK).

The yield of biogas production calculated on the loading food garbage rate was determined by below formula (Thuan and Khanh, 2023)

$$Y = (\sum Vt)/W \tag{1}$$

where: Y – Yield of biogas production (L/kg TS or L/kg VS);
ΣVt – The volume of produced gas produced at time t (L);
W – Weight of loading food garbage in TS (kg) or VS (kg).

Data analysis

SPSS software version 22.0 was used for descriptive statistics for the mean (± stdev) of pH, temperature, Eh, volume of produced biogas, daily produced biogas volume, biogas yield, concentrations of CH_4 and H_2S. One-Way-ANOVA statistical analysis with Duncan test at 95% confidence to compare the mean values of temperature, Eh, volume of produced biogas, daily produced biogas volume, biogas yield, concentrations of CH_4 between treatments. The correlation between the pH and Eh with %TS, volume of produced biogas, and biogas yield was determined by Pearson correlation analysis at p = 0.05.

RESULTS AND DISCUSSIONS

The biogas production under the batch anaerobic digestion

The daily temperature values

The water temperature in the incubation bottle ranged from 23.4 to 27.9 °C (25.5±0.8 °C) (Figure 3). Temperature affects the decomposition of organic matter and the activity of methane-anaerobic bacteria (Chae et al., 2008). There are three possible ranges of temperature in which the anaerobic

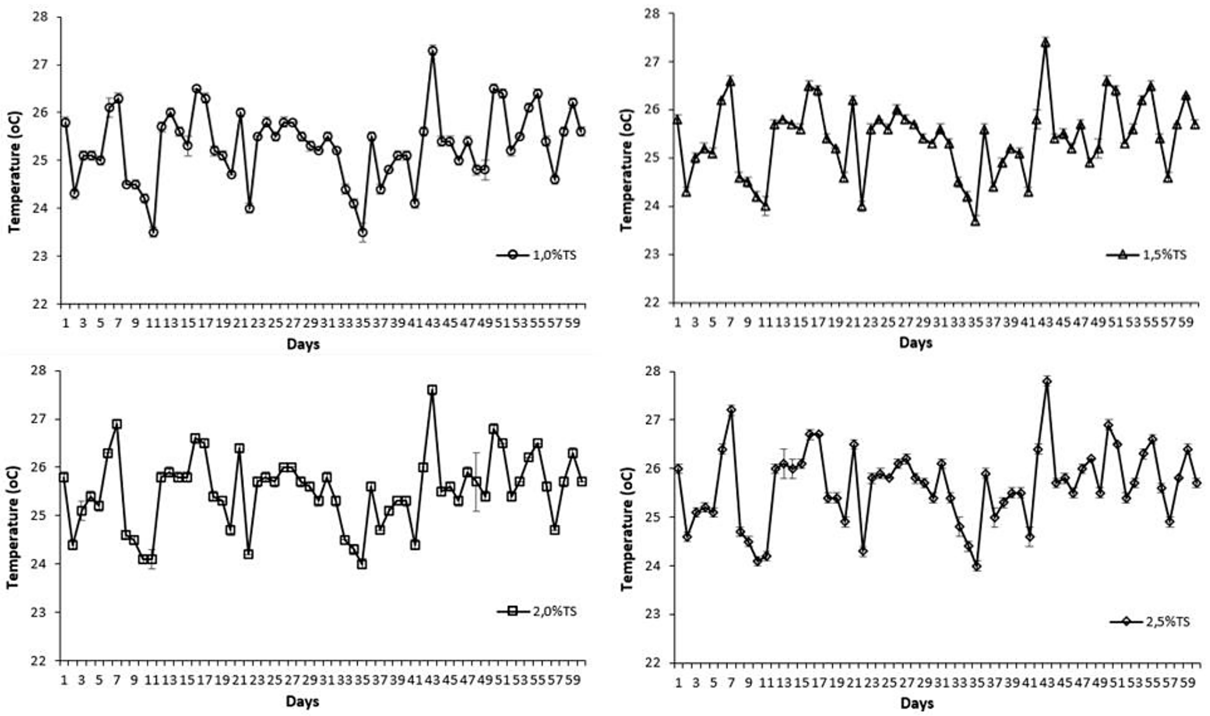

Figure 3. The daily water temperature in the incubation bottle during treatments

digestion can take place under conditions of psychrophilic (15-25 °C), mesophilic (35-40 °C), and thermophilic (50-60 °C) (Sakar et al., 2009). Temperature of 35 °C is typically recommended for CH_4 production (Arikan et al., 2015). The temperature in digesters with kitchen garbage is constant between 38-45 °C during the day and 35-40 °C during the night (Adiotomre and Ukrakpor, 2015).

In general, the temperature range of the experiments was quite favorable for the growth of methane-producing bacteria. Temperature affects biogas production (Arikan et al., 2015; Dupade et al., 2015). Significant differences among treatments were found as recorded temperatures of 25.3±0.8, 25.4±0.8, 25.5±0.8, 25.7±0.8 °C for the treatments of 1.0%, 1.5%, 2.0%, and 2.5%TS, respectively. It suggested that temperature was not a factor for the difference in biogas production in this experiment.

The daily pH values

The results showed that the pH value of all the treatments in the first 10 days tended to be low, only from 3.82 to 4.72 (Figure 4). According to Ramatasa et al. (2014), anaerobic digestion is a four-stage process, including hydrolysis as the first stage, acidogenesis and acidification as the second stage, acetogenesis as the third stage, and methane production as the last stage. At the first and second stages, pH values are low usually due to acidification, and according to Wiese and Konig (2007), for the first and second stages of biogas production, the best pH is between 4.5-6.3. The neutral pH is more efficient for working mesophilic bacteria and a pH of 7.5-8.5 was the operational pH of the digester to achieve more biogas production from kitchen garbage (Falco et al., 2020). However, Ali et al. (2019) reported that methane yield at pH 4.5 was comparable to pH neutral in the experiment of a brewery wastewater treatment plant's anaerobic digester, and lower pH resulted in low biogas yield. To create more suitable pH conditions for incubation, we increased water pH by adding NaOH solution on day 20 and day 30 because the pH value tended to decrease gradually from day 20 to day 30. After adjusting the pH, the pH values in all treatments were greater than 5.0, more stable, and more suitable for methane production conditions. A significant negative correlation between pH values and the loading TS rates was found ($R = -0.875$, $p<0.001$; 5.42±0.11, 5.29±0.13, 5.17±0.03, 5.06±0.06 for treatments of 1.0%, 1.5%, 2.0%, and 2.5%TS, respectively). With a higher loading TS rate, the decomposition of organic matter was more and released more acids, resulting in lower pH values. It found that the pH value for 1.0%TS treatment differed significantly from those for treatments of 2.0%TS and 2.5%TS ($p<0.05$); whereas significant differences among treatments of 1.0%TS and 1.5%TS,

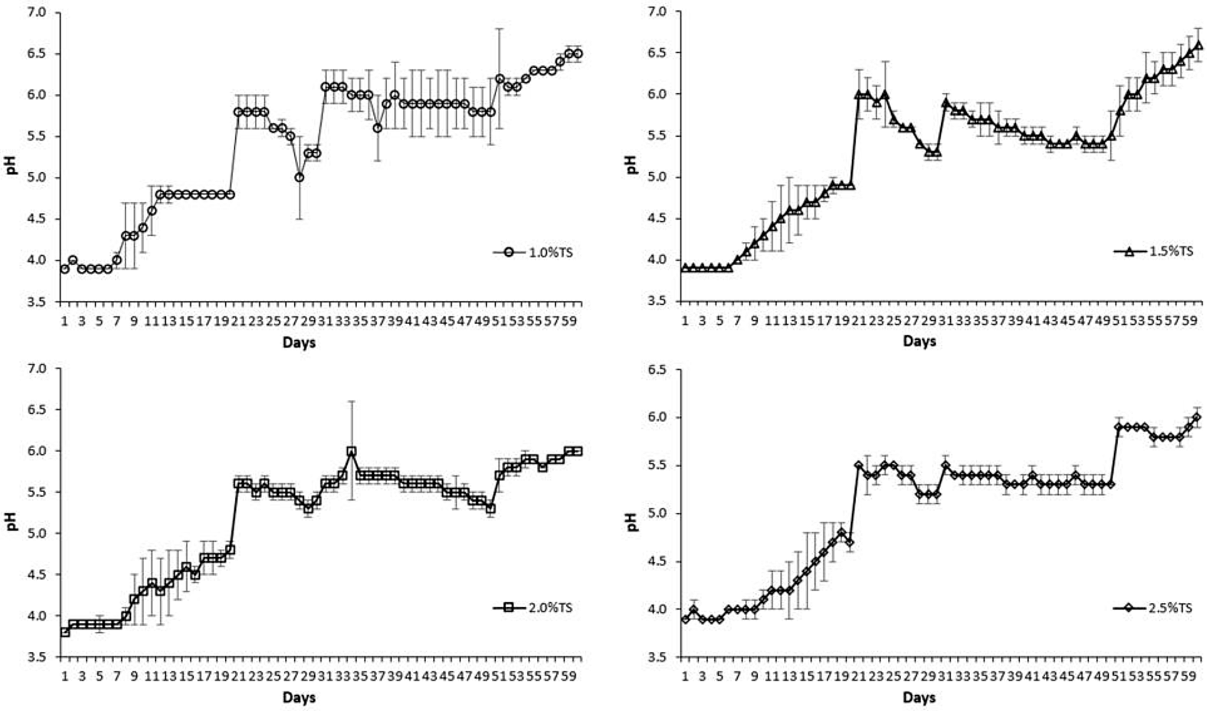

Figure 4. The daily water pH values in the incubation bottle in treatments

treatments of 1.5%TS and 2.0%TS, and treatments of 2.0%TS and 2.5%TS were not found. It implied that pH could differ at varied loading TS rates.

The daily oxidation redox potential values

The Eh values of all treatments ranged from -237.7 to 87 mV (Figure 5). The Eh values of the treatments tend to decrease gradually over time, consistent with the principle that the more anaerobic condition is the smaller the Eh value (Søndergaard, 2009). During anaerobic incubation, anaerobic bacteria consume oxygen in water, resulting responding to the reduction of Eh values (Gerardi, 2003). The more negative Eh value indicated that

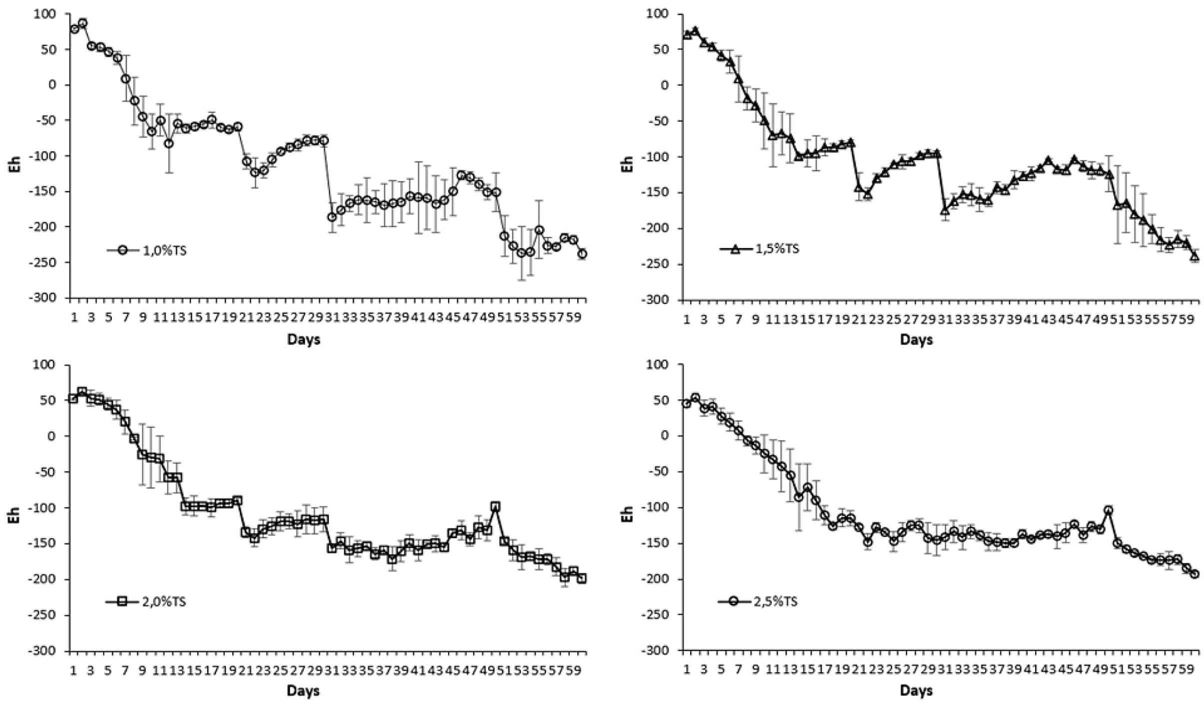

Figure 5. The daily water Eh values in the incubation bottle in treatments

the incubation environment had a high reducing state, and this condition was favorable for the operation of methane-producing anaerobic bacteria.

In this study, the high Eh values during the first 20 days indicated poor reduction, after which Eh values decreased and then stayed stable. In a completely anaerobic environment, the redox potential is always negative with less than -100 mV (Wiese, 2007). Thus, after 20 days, the environmental conditions of the incubations were completely reduced, which is favorable for CH_4 production. It found that the Eh value did not depend on the loading TS rate (R = 0.299, p = 0.345). The differences in Eh values among treatments were not significant, it implied that the Eh values did not cause differences in biogas production in this experiment, and this finding was met with the study of Vongvichiankul et al. (2017).

The produced biogas volumes

The produced biogas volumes within every 10 days (days 1-10, 11-20, 21-30, 31-40, 41-50, and 51-60) and in the sum of 60 days was shown in Figure 6. The biogas volumes in all treatments tended to increase gradually from day 0-10 to day 31-40, the highest on day 31-40, decrease from days 41-50 and drop low on days 51-60. The biogas volume for days 51-60 decreased by 23.9-34.0% compared to days 31-40 with the highest biogas volume. In the early stage, the organic matter was at the beginning of decomposition, so little biogas was produced (Iqbal et al., 2014; Mostafa et al., 2020). After day 10, the process of organic matter was accelerated, leading much biogas being produced. From day 41-60, it is likely that the decomposed-organic matter was little gradually, leading biogas production to decrease gradually. The biogas volume for days 51-60 accounted for 7.7-9.7% of the total biogas volume produced within 60 days, it indicated that almost organic matter was decomposed on days 51-60. The pattern for stages of biogas production under batch anaerobic reaction in this experiment is quite similar to the research with fermented material from kitchen garbage (Iqbal et al., 2014), water hyacinth, and rice straw (Nam et al., 2017) and pig manure (Ngan et al., 2018).

The produced biogas volume within 60 days was positively correlated with the rate of loading TS (R = 0.936, p<0.001), and the relation between biogas volume and loading material was also found in the research of Vikrant and Shekhar (2013). The produced biogas volume between 2.0%TS treatment (2.977±0.288 L) and 2.5%TS treatment (3.150±0.213 L) was insignificantly different (p>0,05); however, they were significantly higher (p<0,05) than 1.0%TS treatment (1.682±0.111 L) and 1.5%TS treatment (2.205±0.204). The relative volumes of daily produced biogas in the treatments of 1.0%TS, 1.5%TS, 2.0%TS, and 2.5%TS were 0.061±0.015 L, 0.070±0.020 L, 0.083±0.019 L, 0.086±0.013 L, respectively.

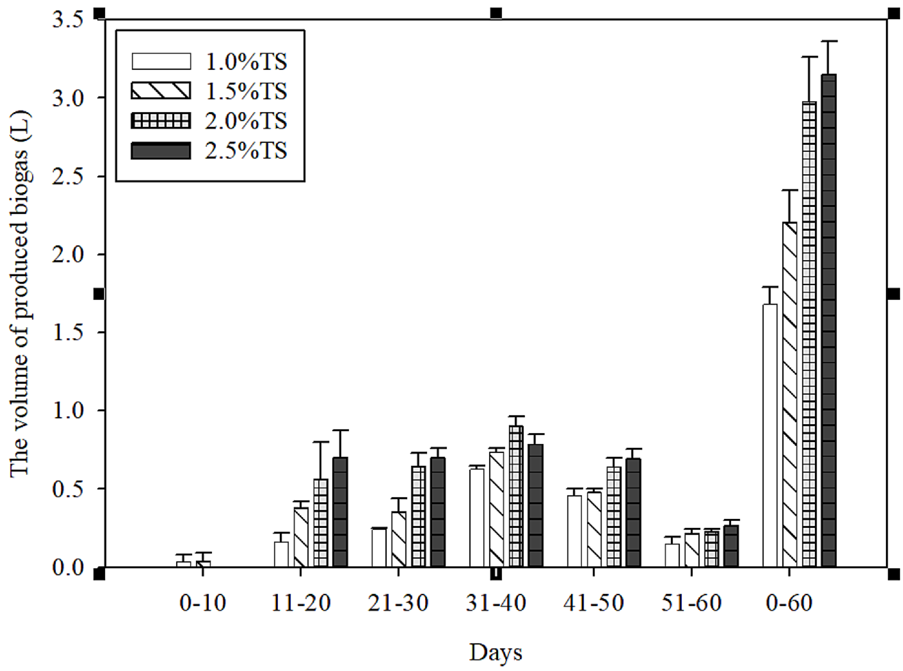

Figure 6. The produced biogas volume every 10 days and in 60 days

The produced biogas yields

The average biogas yields of 1.0%, 1.5%, 2.0%, and 2.5%TS treatments within 60 days were 2.34±0.15 L/kg TS, 2.04±0.19 L/kg TS, 2.07±2.20 L/kg TS, and 1.75±0.12 L/kg TS, respectively (Figure 7). The biogas yield of the treatment 1.0%TS was significantly higher than ($p<0,05$) that of the treatment 2.5%TS. However, insignificant differences among treatments of 1.0%TS, 1.5%TS, and 2.0%TS and among treatments of 1.5%TS, 2.0%TS, and 2.5%TS were found. In actual conditions, too much loading material and decomposition of organic matter causes the accumulation of *soluble* organic acids, leading the low pH, inhibits methane-producing microorganisms (Satoh et al., 2017), and easily clogs incubated system due to the presence of hard-decomposed organic (Karlsson et al., 2014). Meanwhile, with too little loading material, biogas production will be low and not enough volume for the needs of use for cooking households (Viet and Chiem, 2013). Hence, in biogas production, the amount of loading organic matter must be considered (Vikrant and Shekhar, 2013).

The biogas yields of the treatments of 1.0%, 1.5%, 2.0%, and 2.5%TS within 60 days were converted to the loaded VS as 3.64±0.24 L/kg VS, 3.18±0.30 L/kg VS, 5.20±0.50 L/kg VS, and 4.40±0.30 L/kg VS, respectively. The average biogas yield from food garbage is much lower than that of water hyacinth (18.9-23.4 L/kg VS) and rice straw (47.7-70.4 L/kg VS) with a similar designation of experiments (Nam et al., 2017). The hard-decomposed organic components in food garbage can be higher than that of water hyacinth, resulting in a lower biogas yield from food garbage compared to water hyacinth. The low biogas yield from food garbage in this experiment compared to rice straw could be caused by low pH in the early stage of the experiment of food garbage. For better comparison, it is necessary to have research on biogas production from other loading materials with the same experimental designation.

The methane concentrations

On days 1-20, a percentage concentration of CH_4 was not detected in all treatments (Figure 8). This can be interpreted due to unsuitable and low conditions of pH and high redox potential for CH_4 production in the first 20 days as discussed above. After day 20, the pH and Eh became more and more suitable, so the CH_4 produced also increased gradually. Such a trend of low CH_4 concentration in the early stage of incubation was found in the reported research (Nam et al., 2017; Iqbal et al., 2014; Mostafa et al., 2020). In general, the percentage concentration of CO_2 was low compared to the concentration of CH_4 and other gas; and other gas tended to reduce over time. Inversely, CH_4 concentration tended to increase over time, and the trend was matched with research on CH_4 production from water hyacinth and rice straw (Nam et al., 2017).

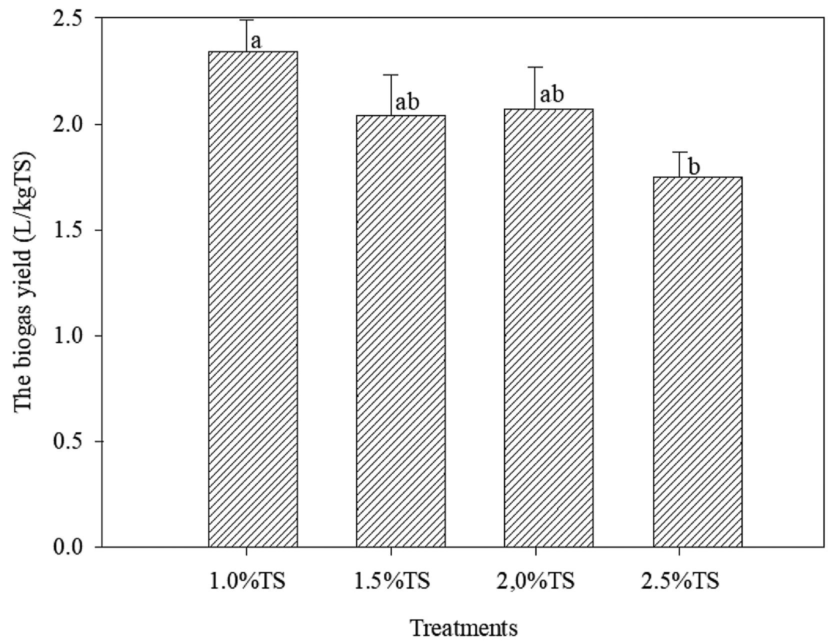

Figure 7. The biogas yield of the treatments. The different letters in the figure indicated significant differences in the biogas yield at the level p = 0.05

The percentage concentration of CH_4 was correlated insignificantly with the amount of loading TS (R = 0.825, p>0,05) (24.98±5.11%, 33.18±9.91%, 36.10±10.07%, and 34.58±12.29% CH_4 for treatment of 1.0%, 1.5%, 2.0%, and 2.5%TS, respectively). The CH_4 concentration of the treatment 2.0%TS was significantly higher than those for treatments of 1.0%TS, and 1.5%TS; but was insignificantly different from those for 2.5%TS treatment. The significant differences among treatments were 1.0%TS, 1.5%TS, and 2.5%TS.

Results from the experiment on the biogas production under the batch anaerobic reaction showed that the biogas yields for treatments of 1.0%TS, 1.5%TS, and 2.0%TS were better than those for treatment of 2.5%TS; however, CH_4 percentage concentrations were better for treatments 2.0%TS and 2.5%TS. Thus, in the experiment on the biogas production under semi-continuous anaerobic reaction, we considered treatments with loading TS rate as same as the batch anaerobic reaction.

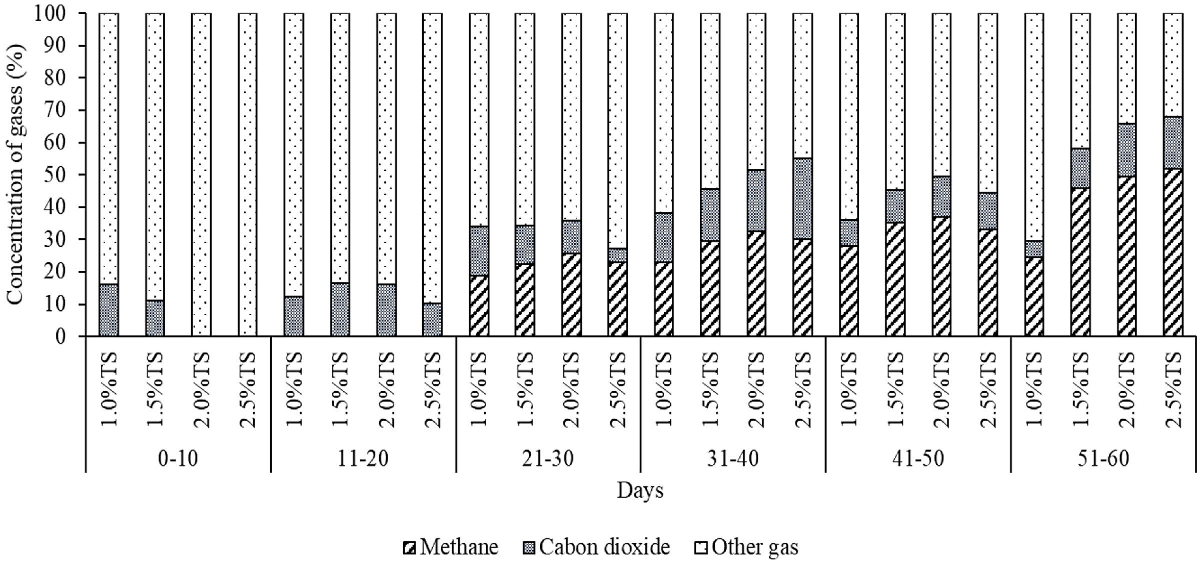

Figure 8. Percentage concentrations of CH_4, CO_2 and other gases

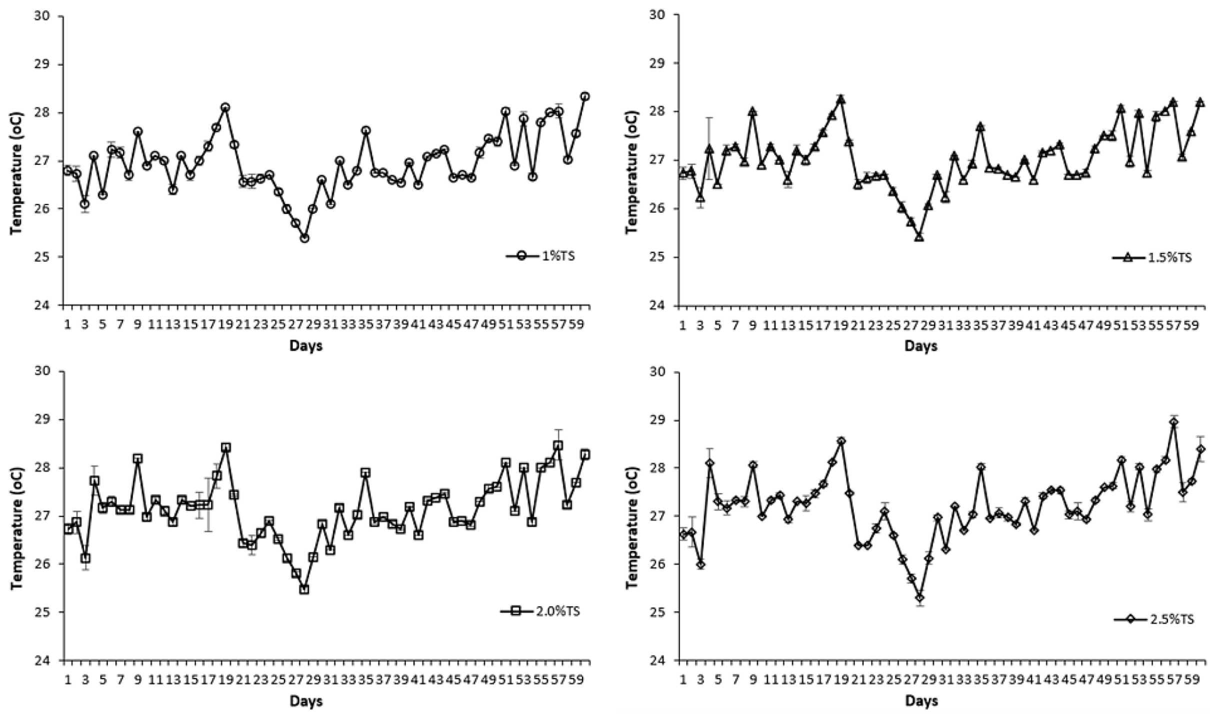

Figure 9. Daily temperature in the semi-continuous anaerobic reactors

The biogas production under the semi-continuous anaerobic reaction

Conditions of temperature, pH, and Eh for biogas and CH_4 production

The average value of temperature in substrate in reactions was 27.08±0.65 °C (25.1-29.1 °C) (Figure 9), which was quite suitable for CH_4 production. The average value of pH in substrate in reactions was 5.10±0.18 (4.71-6.36) (Figure 10). Although pH values were not in the optimum range for fermentation-producing CH_4, they were quite suitable to promote CH_4 production. The Eh values after the fifth day remained below - 100

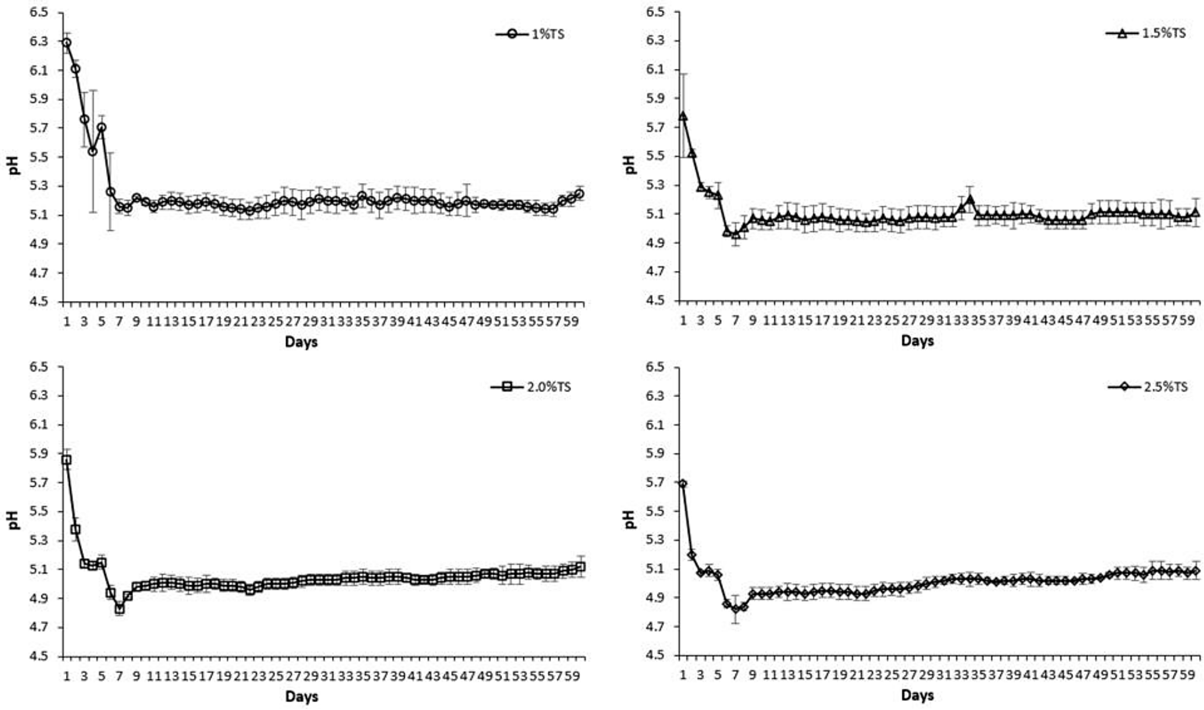

Figure 10. pH values in the semi-continuous anaerobic reactors

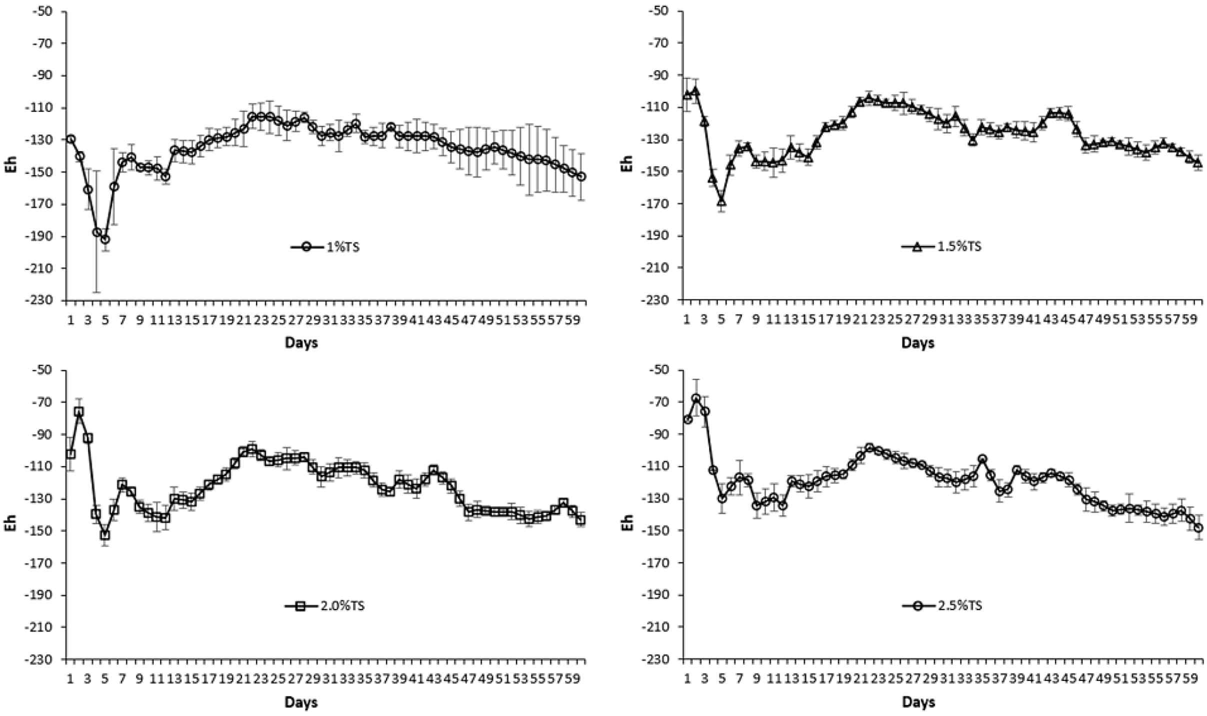

Figure 11. Eh values in the semi-continuous anaerobic reactors

mV (Figure 11), which is a suitable condition for anaerobic fermentation to produce CH_4. In general, conditions of temperature, pH, and Eh were controlled with the suitable condition for CH_4 production in the experiment of biogas production under the semi-anaerobic digesters.

The volumes of daily produced biogas

The daily produced biogas volumes could be divided roughly into three stages. In the first stage of the first ten days, produced biogas volumes were small and not stable and the reasons for the low volumes of produced biogas at this stage were an explanation for the produced biogas in the experiments of the batch anaerobic reactors. The total biogas volumes produced in the first ten days were 0.273±0.020 L, 0.407±0.064 L, 0.535±0.049 L, and 0.643±0.066 L for treatments of 1.0%, 1.5%, 2.0%, and 2.5%TS, respectively. The produced biogas volumes were high at the stage of days 11 to 45. After day 45, it is the stage of biogas volumes were produced gradually due to substrates stopped loading (Figure 12). In general, daily produced biogas volumes in all treatments had a trend of gradual increase from the beginning of the experiment to day 45 because the organic matter was cumulated gradually until day 45. Such a trend was matched with the trend of biogas production from water hyacinth from day 1 to day 45 as studied by Thuan and Khanh (2023).

The produced biogas volumes depended on loaded %TS as seen in the experiment of batch anaerobic reaction and the previous study on biogas production from water hyacinth in the condition of semi-continuous anaerobic reaction (Thuan and Khanh, 2023). The total produced biogas volumes correlated positively with loaded TS ($R = 0.998$, $p = 0,02$), which was the lowest volume for the treatment of 1.0%TS and the highest volume for the treatment of 2.5%TS (Table 4). Similarly, daily produced biogas volumes increased gradually from the treatment of 1.0%TS to the treatment of 2.5%TS. The daily produced biogas volume was dependent on the loading TS% rate. The daily produced biogas volumes in the stable stage of biogas production from day 11 to day 50 were 0.180±0.019 L/day, 0,280±0.017 L/day, 0.415±0.025 L/day, 0.565±0.008 L/day for treatments of 1.0%, 1.5%, 2.0%, and 2.5%TS, respectively.

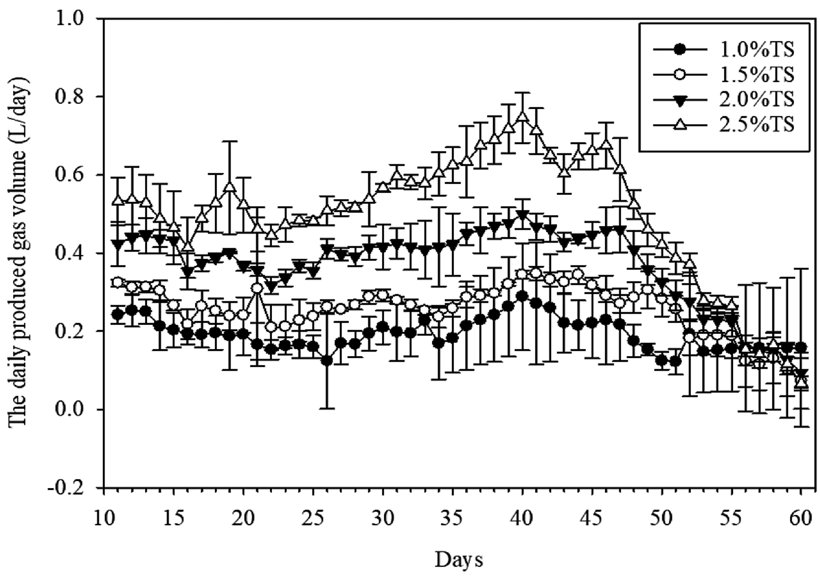

Figure 12. The changes in the daily produced biogas volumes within semi-continuous reactors

Table 4. Biogas volumes and yields observed through 45 days of the experiment

Treatments	Total biogas volume produced within 45 days (L/45 days)	Daily biogas volume produced within 45 days (L/day)	Biogas yield by TS within 45 days (L/kg TS)	Biogas yield by VS within 45 days (L/kg VS)
1.0%TS	6.564 ± 0.666[a]	0.146 ± 0.015[a]	0.644 ± 0.167[a]	1.201 ± 0.122[a]
1.5%TS	10.208 ± 0.618[b]	0.227 ± 0.014[b]	0.945 ± 0.057[b]	1.245 ± 0.075[ab]
2.0%TS	15.052 ± 0.929[c]	0.334 ± 0.021[c]	1.045 ± 0.065[b]	1.377 ± 0.085[ab]
2.5%TS	20.420 ± 0.350[d]	0.454 ± 0.008[d]	1.134 ± 0.019[b]	1.495 ± 0.026[b]

The biogas yields within 45 days of continuous loading of food garbage based on %TS among the treatments of 1.5%TS, 2.0%TS and 2.5%TS were insignificant difference (p>0,05); however, their biogas yields differed significant compared with the treatment 1.0%TS (Table 4). Regards the biogas yields calculated by %VS, the biogas yields of the treatment 2.5%TS was significantly higher than the treatment 1.0%TS. The significant differences among the treatments of 1.0%TS, 1.5%TS, and 2.0%TS and among the treatments of 1.5%TS, 2.0%TS, and 2.5%TS were not found. In general, with condition of semi-continuously loading of food garbage, the biogas yields tended to be higher at higher loading TS%. This result is similarity to the finding of Vikrant and Shekhar (2013) that anaerobic reactor can treat food garbage with high food garbage load.

The average biogas volume that is enough for cooking of one household in rural areas in Vietnam is 0.74 m^3/day (Nam et al., 2022). At the loading rate of 2.5%TS, daily biogas volume produced at day 45 was 0.661 L/day which was below the demand of households. Thus, to meet with biogas use of households, it is necessary to consider (i) to select at higher loading rate of %TS or (ii) improve condition of cooking stove with gas saving. Another aspect is that the amount of food garbage disposed from every household in the Vietnamese rural areas is very low (Thuan and Thanh, 2022), so that to produce enough biogas demand for households, collection of food garbage from small community should be considered (Chiem et al., 2021). It means the higher loading rates of food garbage should be examined. Additionally, in consideration of circular economy, research on the mix between food garbage and other available materials in rural areas such as animal wastes, green biomass, agricultural by-products and so on should be carried out to explore benefits of biogas production at household or community scale (Holmberg at el., 2021).

The methane production

There was a trend of increase of the percentage concentrations of CH_4 when increasing the %TS loaded, in which 25.72%, 26.14%, 27.92%, and 29.65% were average percentages of CH_4 for treatments of 1.0%, 1.5%, 2.0%, and 2.5%TS respectively. The percentage concentrations of CH_4 tended to increase with time which is matched with previous studies (Nam et al., 2017; Thuan and Khanh, 2023). The %CH_4 concentrations in all treatments were higher in the last stage from day 45 although biogas production was reduced in this stage; the percentage of CO_2 concentrations in all treatments were high in the stage of stable biogas production from day 11 to 45, when organic matter was decomposed largely, whereas, other gases were high at the first stage due to little organic matter decomposed to release CO_2 and CH_4 (Figure 13). The percentage concentrations of CH_4 that can be used for cooking should be at least 45% (Ngan et al., 2018; Nam et al., 2022). The percentage concentrations of CH_4 at day 60 for the treatments of 2.0% (43.6%) and 2.5% (41.7%) were a little lower than 45%. Thus, it is suggested that in the respect of the CH_4

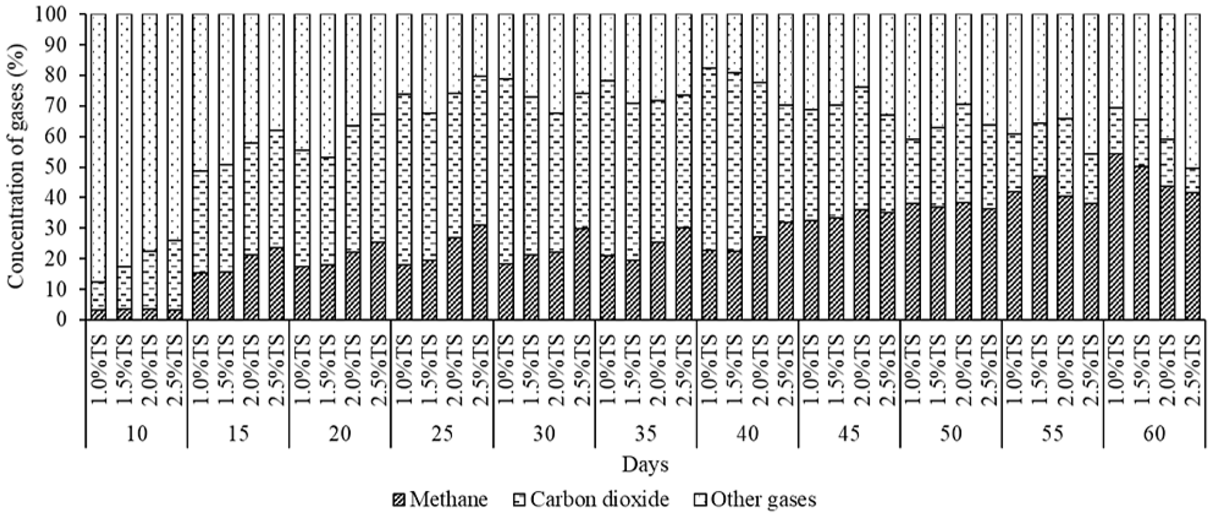

Figure 13. Concentrations of CH_4, CO_2 and other gases produced in biogas between treatments

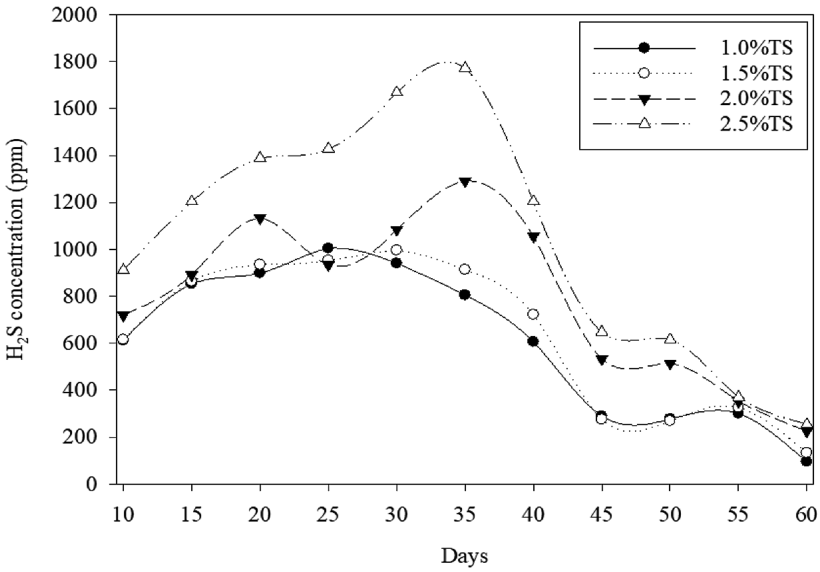

Figure 14. Concentrations of H_2S in biogas between treatments

component, biogas can be used for cooking from day 60 of the fermentation of food garbage.

The concentration of H_2S tended to increase gradually from the beginning day to day 35, and then gradually decrease (Figure 14). After day 35, the change in H_2S concentration tended to be opposite to that of CH_4 concentration. In fact, the concentrations of H_2S tended to be higher in the treatments with higher %TS loading rates which were 607.6±319.3 ppm, 636.6±327.3 ppm, 794.1±348.7 ppm, and 1042.1±517.3 ppm for treatments of 1.0%, 1.5%, 2.0%, and 2.5%, respectively. As a higher %H_2S values were recorded in this experiment, the reduction of H_2S should be considered when using food garbage for biogas production. The higher %H_2S concentration, the more toxic, and corrosive contaminant in biogas, thus its removal is a necessary condition for any energy conversion system (Hao et al., 2020; Monteleone et al., 2011). Even at low concentrations, the presence of H_2S is undesirable during energy production mainly due to its corrosiveness. The recommended concentration of H_2S for combustion is less than 500 ppm (Fortuny et al., 2008). Thus, with the food garbage treatments with concentrations greater than 500 ppm, the use of biogas requires a longer anaerobic incubation time.

CONCLUSIONS

The research found that the volume of biogas produced from food garbage depended on the loading rates of food garbage. The pH value was a determining factor that significantly affected the volume of biogas produced but was not account for temperature and the oxidation-reduction potential. The pH values tended to be higher at higher loading rates, which cause inhibited biogas production, therefore, the factor of pH must be considered controlling when applying practically. Additionally, to increase the high yield of produced biogas, the mixing of food garbage during anaerobic digestion should be considered. At loading 2.5%TS of food garbage, produced biogas volume was near to meet the demand of daily gas use by households and the percentage concentration of CH_4 in biogas at 60 days of incubation was a little lower than the lowest threshold of CH_4 concentration can be burned. Therefore, a study with higher-loading food garbage and a longer time of incubation needs to be carried out. Another finding is that H_2S concentration in biogas was very high which must be reduced to use biogas for cooking effectively. Finally, able to be practiced in households, it is necessary to consider mixing food garbage with other materials to increase biogas production and to be unsure of adequate loading material for a single household or small community.

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