RESERCH ARTICLE **Open Access**

Gema Lingkungan Kesehatan
Vol. 22, No. 2 (2024), pp 95-102
e-ISSN 2407-8948 p-ISSN 16933761
Doi: https://doi.org/10.36568/gelinkes.v22i2.185 *Journal Hompage: https://gelinkes.poltekkesdepkes-sby.ac.id/*

Utilization of Liquid Waste from Tofu Production Using Anaerobic Methods for Biogas

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ABSTRACT

Liquid waste is a significant problem in environmental control. Waste discharged into water bodies will inevitably pollute the surrounding water body, disrupting the life of living organisms nearby. The tofu industry on Jalan Bangka VII Pela Mampang, Mampang Prapatan Subdistrict, South Jakarta, produces liquid waste collected in waste tanks and discharged directly into water bodies without prior treatment. This causes visible turbidity in the water bodies and foul odors from the tofu industry's liquid waste, which can disturb nearby residents aesthetically and due to the potential emergence of diseases. Tofu liquid waste can be treated biologically or chemically. Anaerobic biological treatment can be about 70% efficient. This research aims to determine how to treat liquid waste in the tofu industry using a plug-flow reactor. The biogas production methodology involves three stages. Stage I involves preparing a set of biogas digesters. Stage II involves mixing tofu liquid waste and EM4 in a 1:1 weight ratio and placing it in the digester, followed by analyzing the raw materials, including COD, BOD, pH, and acetic acid analysis. Stage III involves a continuous fermentation process in the digester for 60 days with variables including HRT (Hydraulic Retention Time) of 30, 20, and 10 days of operation and temperature control to keep the fermentation conditions constant at 30°C. Therefore, appropriate and effective HRT and OLR (Organic Loading Rate) are needed to produce biogas from tofu liquid waste. In this study, the researcher will use a digester for 60 days to produce biogas from the tofu factory's liquid waste.

Keywords: Tofu waste, Biogas, Anaerobic, Energy

INTRODUCTION

The tofu industry generates two types of waste during its processing: solid and liquid. Solid waste, such as tofu dregs, is produced during the filtration of soybean slurry. This solid waste is sold and processed by the producer into tempe gembus, tofu dregs crackers, animal feed, and tofu dregs flour, which is used as a base material for dry bread (Subekti, 2011). Liquid waste is produced by washing, boiling, pressing, and molding. On average, the raw materials for tofu production per day range from 100 to 300 kg, depending on demand (Rajagukguk, 2020). From 100 kg of soybeans, about 800 liters of liquid waste are generated daily. Tofu liquid waste contains high levels of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and acidity (pH) (Anggraini et al., 2015). The composition of tofu liquid waste is mostly water (99.9%), with the remaining 0.1% consisting of dissolved and suspended solid particles (Sayow *et al.*, 2020). The solid particles are composed of organic substances (approximately 70%) and inorganic substances (approximately 30%). Organic substances include 1% carbohydrates (mainly stachyose and sucrose), 0.1-0.8% protein, 0.4-1.0% fat, and around 0.4% minerals (Paramita, Shovitri and Kuswytasari, 2012).

The liquid waste produced by the tofu manufacturing industry is a thick liquid separated from the clumps of tofu water, called whey, which contains high protein and can decompose quickly (Novi Darmayanti, Isnaini Anniswati R and Dian Viola Kartka Sari, 2021). This waste is often discharged directly without prior treatment, causing foul odors that pollute the environment. The solid waste from tofu processing includes dirt from soybean cleaning, such as stones, soil, soybean skins, and other solid materials attached to the soybean skin, as well as residue from the soybean slurry filtration called tofu dregs (Ratnani, 2011). Solid waste from the initial process or raw soybean washing is generally minimal, about 0.3% of the raw soybean material (Yudhistira, Andriani and Utami, 2018). Solid waste in the form of tofu dregs is produced during the soybean slurry filtration process, constituting about 25-35% of the resulting tofu product.

The composition of tofu liquid waste is mostly water (99.9%), with the remaining 0.1% consisting of dissolved and suspended solid particles. The solid particles are composed of organic substances (approximately 70%) and inorganic substances (approximately 30%). Organic substances include 1% carbohydrates (mainly stachyose and sucrose), 0.1-0.8% protein, 0.4-1.0% fat, and around 0.4% minerals (Nisrina and Andarani, 2018).

Liquid waste discharged directly into the surrounding environment causes numerous environmental problems. Figure 2 illustrates that tofu liquid waste if directly discharged into water bodies, will reduce the environmental carrying capacity, necessitating waste treatment processes in the tofu industry to mitigate pollution risks (Lesharnoto, 2014). Waste directly discharged into the surrounding environment leads to environmental and public health issues. Communities around tofu processing industries frequently complain about pollution from tofu waste disposal. Environmental pollution issues include air and water pollution and cleanliness problems in the affected villages. The liquid waste from tofu factories has a high organic compound content (12). Without proper treatment, tofu waste causes negative impacts such as water pollution, disease vectors, unpleasant odors, increased mosquito growth, and reduced aesthetic value of the surrounding environment (Anis Maryati , Umi Octaviana, 2014).

Many household-scale tofu factories in Indonesia do not have liquid waste treatment processes. The reluctance of tofu factory owners to treat their liquid waste is due to the complex and inefficient treatment processes, which do not provide added value. However, tofu factory liquid waste has a high organic compound content that has the potential to produce biogas through anaerobic processes. By converting tofu factory liquid waste into biogas, tofu factory owners can contribute to environmental conservation and increase their income by reducing fuel consumption in the tofu production process. Generally, biogas contains 50-80% methane, CO_2, H_2S, and a small amount of water, which can be used as a substitute for kerosene or LPG (Ridhuan, 2016).

Based on field observations, several household-scale tofu factories located in Tofu Factory Pela Mampang do not have liquid waste treatment processes. Due to the complex and inefficient treatment processes, many tofu factory owners are unwilling to treat their liquid waste. Some reasons for not treating the liquid waste include limited funds to build and operate wastewater treatment plants, lack of waste treatment technology for small industries, entrepreneurs not seeing the benefits of liquid waste treatment, low environmental awareness among the community, and the non-immediate impact of waste disposal on the environment, making the community seemingly resistant (Azhari, 2014).

Another issue for tofu industry practitioners is their inability to utilize tofu waste as an alternative energy source (renewable energy) to replace wood and fuel oil, as their daily activities heavily depend on gas and wood for cooking. This significantly affects the income of the tofu industry practitioners (Savitri, Nugraha and Aziz, 2016).

Biogas, as an alternative energy source, has several advantages over fossil-based fuels. It is environmentally friendly and renewable. Additionally, biogas has an energy content comparable to fossil fuels. Therefore, biogas is well-suited to replace kerosene, LPG, and other fossil fuels (Kurniawan and Auliyah, 2015). Biogas can be sourced from various materials, including livestock manure, rice straw, water hyacinth, tofu industry waste, jatropha seed cake, and other sources (Haryati, 2006).

Biogas is generated from household waste, animal manure, human waste, organic waste, and other materials that undergo decomposition or fermentation of organic matter by anaerobic bacteria. Anaerobic waste treatment produces biogas composed of CO_2 and CH_4. Gas production also depends on the performance of methanogenic bacteria, influenced by pH, temperature, nutrient content, and retention time. Biogas energy is obtained through the anaerobic digester method. This method employs various microbes that convert biomass and waste into biogas by degrading organic materials without oxygen, aided by bacteria (Jurnal, 2017). The anaerobic process suits liquid waste containing complex organic matter, such as waste from the food, beverage, chemical, and pharmaceutical industries. This organic matter is degraded into simple and stable compounds through four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Indriyati, 2018).

Biogas primarily comprises CH_4 (methane gas), which has significant potential as an energy source for cooking, heating, or conversion into electricity. The components of biogas produced from the fermentation process include methane gas (CH_4) at approximately 54-70%, carbon dioxide (CO_2) at around 27-45%, nitrogen (N_2) at 3-5%, hydrogen (H2) at 1%, carbon monoxide (CO) at 0.1%, oxygen (O2) at 0.1%, and a small amount of hydrogen sulfide (H_2S). Methane gas (CH_4), the main component of biogas, is a valuable fuel due to its high calorific value, which ranges from 4800 to 6700 kcal/m³. Due to its high calorific value, biogas can be used for lighting, cooking, driving engines, and more. Biogas is the final product of the anaerobic process, with the main components being CH_4 and CO_2, along with H_2, N_2, and other gases such as H_2S (Kurniati *et al.*, 2021).

Each cubic meter of biogas is equivalent to half a kilogram of liquid petroleum gas (LPG), half a liter of gasoline, or half a liter of diesel oil. Biogas can generate electrical power ranging from 1.25 to 1.50 kilowatt-hours (kWh). A biogas reactor that produces methane gas must convert tofu factory liquid waste into biogas. Utilizing tofu waste to produce biogas is expected to reduce environmental pollution and make liquid waste economically valuable and environmentally friendly (Triyatno, 2018).

Planning a biogas reactor is crucial and determined by several factors: the waste material used to produce biogas, the construction of the biogas reactor, location, reactor capacity, and cost (Ambar Pertiwiningrum, 2015). There are many challenges in developing biogas technology, including the lack of technical expertise. Many biogas reactors fail due to construction errors. Designs that do not meet user needs can lead to various problems.

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There are various biogas energy sources, including animal manure, rice straw, water hyacinth, tofu industry waste, jatropha seed cake, and many others. Therefore, it is necessary to process tofu waste into biogas as an energy source and address the issue of liquid tofu waste. In this research, the researcher will use a Portable Biogas Reactor to convert tofu factory liquid waste into biogas at the tofu industry located on Jalan Bangka VIII Pela Mampang, Kecamatan Mampang Prapatan, South Jakarta. The results of this study are expected to demonstrate that biogas from tofu waste can be used effectively as an alternative solution to address water body pollution caused by tofu factory waste.

METHOD

The process of producing biogas from tofu factory waste was carried out at the Waste Treatment Chemical Engineering Laboratory Workshop, Environmental Health Department. This biogas innovation was developed from tofu waste over four months, from August to September 2021. The materials used in this process were tofu waste and EM4. EM4 is an effective microorganism derived from cow dung, cow rumen, or indigenous bacteria from the waste. These decomposer microorganisms include Streptococci, Bacteroides, Methanobacterium, Desulfovibrio, Methanobacillus, Methanosarcina, and Methanococcus.

The equipment used for the biogas innovation includes:

A. Digester
B. Filter paper
C. Erlenmeyer flask
D. Measuring glass
E. Funnel
F. Bucket

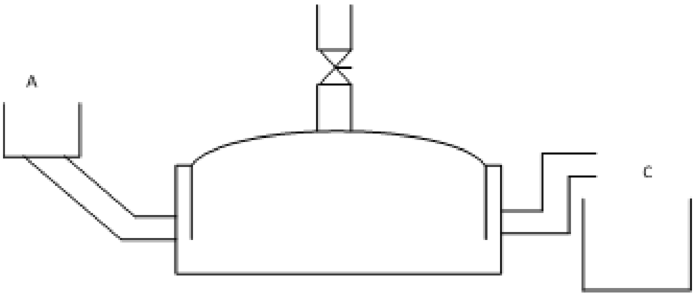

Figure 1. Biogas Equipment Scheme

The experimental variables in this study aim to determine the Hydraulic Retention Time (HRT) values of 3, 6, and 9 days with varying Organic Loading Rates (OLR).

The preparation phase involved a literature review related to research design, focusing on the characteristics of tofu waste. After studying these characteristics, the next step was to define the variables and operational conditions. Observations were also made in the Waste Processing Laboratory of the Chemical Engineering D3 Program at FV-ITS. Equipment was prepared and standardized in the preparation phase, including tying plastic bags for biogas collection, using a 1000 mL measuring cylinder for weighing materials, and calibrating an electronic scale to zero. The biogas production process began by preparing EM4, mixed with distilled water in a 1:2 ratio, and added to the reactor. Tofu waste was then introduced into the reactor and incubated for 24 hours. Water was prepared in a container to analyze the biogas, and the measuring cylinder was filled with water and immersed in the container. The biogas was then transferred into the measuring cylinder for analysis. The analysis phase involved measuring the volume of biogas daily. This was done by preparing water in a container, filling a 1000 mL measuring cylinder with water, immersing it in the container, and transferring the collected biogas from the plastic balloon into the measuring cylinder for content analysis.

The population for this study consisted of liquid waste from tofu production. At the same time, the sample was tofu liquid waste containing biogas from the tofu industry on Jalan Bangka VII Pela Mampang, Mampang Prapatan, South Jakarta. The tofu liquid waste sample was murky, light yellow, had an odor, and contained white suspensions.

RESULT AND DISCUSSION

In this study, biogas production was investigated by analyzing the effects of Hydraulic Retention Time (HRT) of 7, 14, and 21 days on biogas production using a portable plug flow reactor. The results of the volume of biogas obtained at different HRT values are presented in Table 2.

Table 2
Volume of Biogas Produced during HRT of 7, 14, and 21 Days

Hari	Biogas Volume (mL)		
	HRT 7 Days	HRT 14 Days	HRT 21 Days
1	530	400	400
2	250	510	450
3	250	495	0
4	350	450	0
5	425	500	300
6	450	490	280
7	500	500	350
8		350	0
9		450	320
10		500	0
11		490	0
12		485	350
13		490	370

14		500	0
15			415
16			0
17			425
18			0
19			0
20			300
21			325
Mean	474,761	488,333	512,380

The effect of Hydraulic Retention Time (HRT) of 7 Days on biogas volume over 7 days is shown in Figure 2.

Figure 2. Effect of Hydraulic Retention Time (HRT) of 7 Days on Biogas Volume over 7 Days

Anaerobic degradation involves a variety of bacteria, but it is primarily driven by two types of reactions: acidogenesis and methanogenesis (Zoetemeyer, Van den Heuvel and Cohen, 1982; Baloch *et al.*, 2008). In the first stage, acidogenic bacteria break down organic material into volatile fatty acids (VFA), which are then metabolized into methane in the subsequent stage by methanogenic bacteria to produce methane gas (biogas).

Figure 2 illustrates the biogas volume produced over 21 days with an HRT of 7 days. The average daily biogas production volume is 393.57 mL. The graph shows fluctuations in gas volume from day to day.

These fluctuations are inconsistent with literature expectations and can be attributed to the sensitivity of the anaerobic process to microbial activity. Variations in biogas production are influenced by the activity of microorganisms, which can experience fluctuations and be hindered by factors such as air contamination. Oxygen can inhibit the growth of methanogenic bacteria, which are obligate anaerobes, leading to reduced biogas production or even bacterial death (Dueblein and Steinhauser, 2008).

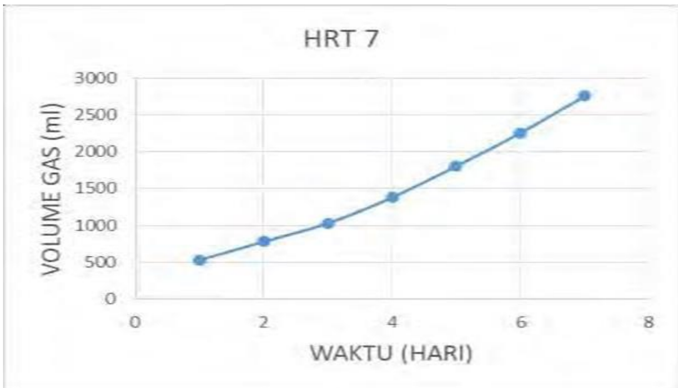

Figure 3. Effect of Hydraulic Retention Time (HRT) of 7 Days on Accumulated Biogas Volume

Figure 3 shows the accumulated biogas production with an HRT of 7 days. The results indicate that biogas production increased as the days progressed.

Figure 4. Effect of Hydraulic Retention Time (HRT) of 14 Days on Biogas Volume Produced over 14 Days

The anaerobic degradation process involves a wide range of different bacteria, but it is primarily driven by two types of reactions: acidogenesis and methanogenesis (Zoetemeyer, Van den Heuvel and Cohen, 1982; Baloch *et al.*, 2008). In the first stage of acidogenesis, organic materials are broken down into volatile fatty acids (VFA), which are then metabolized into methane in the subsequent stage by methanogenic bacteria to produce methane gas (biogas). Figure 4 is based on an HRT of 14 days with the biogas volume produced from Day 1 to Day 21. The average daily gas production volume is 472.14 mL. The graph shows fluctuations in gas volume, with a maximum volume of 650 mL on Day 3 and subsequent decreases in biogas volume until Day 14. These fluctuations are inconsistent with the literature because the anaerobic process is highly dependent on microbial activity, which is prone to variations. According to research by Li *et al.*, (2014), fluctuations in microbial communities can be caused by changes in environmental conditions such as temperature, pH, and substrate concentration. They found that sudden changes in operational parameters could lead to a decrease of up to 30% in methane production. In line with this, Jiang *et al.*, (2019) observed that the stability of the anaerobic process heavily depends on the balance between various microbial groups, particularly between acid-producing bacteria and methanogenic archaea. Additionally, air contamination can hinder the growth of biogas-producing bacteria (methanogenic bacteria), which are obligate anaerobes, and may even lead to their death (Dueblein and Steinhauser, 2008).

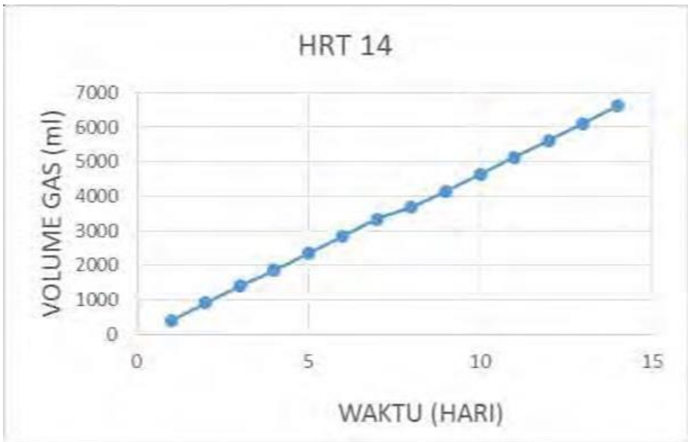

Figure 5. Effect of Hydraulic Retention Time (HRT) of 14 Days on the Accumulated Volume of Biogas Produced

Figure 5 shows the accumulated biogas production at an HRT of 14 days. The results indicate that biogas production increased as the days progressed.

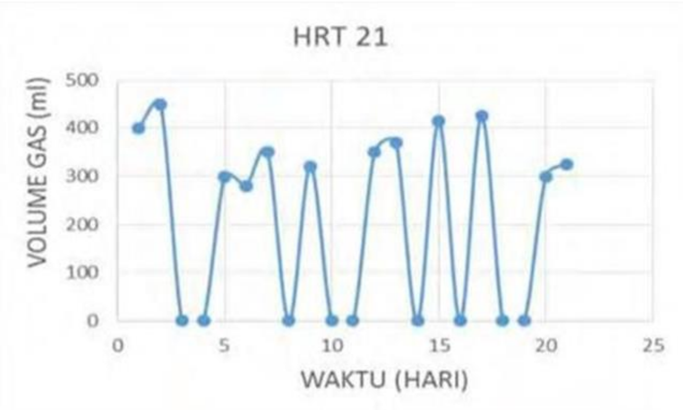

Figure 6. Effect of Hydraulic Retention Time (HRT) of 21 Days on the Volume of Biogas Produced

The anaerobic degradation process involves various bacteria, but it is primarily driven by two types of reactions: acidogenesis and methanogenesis (Zoetemeyer, Van den Heuvel and Cohen, 1982; Baloch *et al*., 2008). In the acidogenic phase, organic materials are broken down into volatile fatty acids (VFAs), which are then metabolized into methane in the subsequent phase by methanogenic bacteria to produce methane gas (biogas). Research indicates that the acidogenic phase plays a crucial role in the anaerobic digestion process. According to a study by Detman *et al.*, (2021), VFA products from the acidogenic stage significantly impact methane production efficiency in the methanogenic stage. Figure 6 is based on an HRT of 21 days, showing the volume of biogas produced from day 1 to day 21. The average daily gas production volume is 204.04 mL. The graph displays highly fluctuating increases and decreases in daily gas volume.

Figure 6's fluctuations in gas volume do not align with the literature because the anaerobic process is highly dependent on microbial activity, which is very susceptible to fluctuations. Additionally, air contamination can hinder the growth of biogas-producing bacteria (methanogenic bacteria), which are obligate anaerobes, potentially leading to growth inhibition or even death (Dueblein and Steinhauser, 2008).

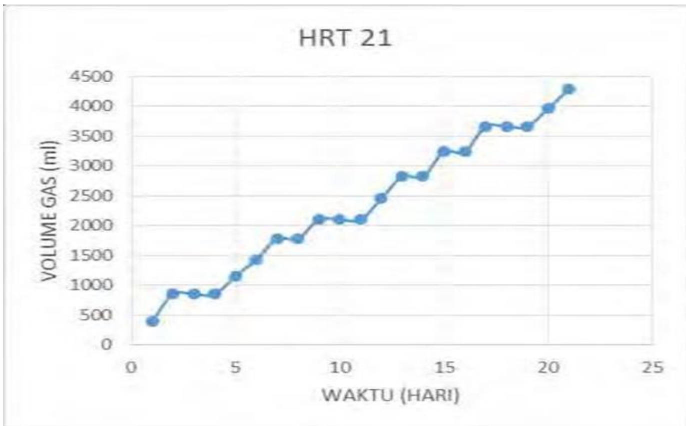

Figure 7. Effect of Hydraulic Retention Time (HRT) 21 Days on Accumulated Biogas Volume

Figure 7 shows the cumulative biogas production for an HRT of 21 days. The results indicate that biogas production increases with the passing days. The research also demonstrates that biogas production is stable after a certain fermentation period but continues to increase slowly. For instance, analysis by the International Energy Agency (IEA) indicates that while the increase in biogas production is more significant in the early stages, the production rate still shows moderate increases over time, mainly when organic materials are fully decomposed (International Energy Agency, 2020). On average, the biogas production is 201.04 mL per day. From the average biogas production results with HRTs of 7, 14, and 21 days, it can be observed that biogas is produced optimally at an HRT of 14 days, with an average of 472.14 mL.

Effect of HRT on Final pH Value After Fermentation. The final pH values after the fermentation process are presented in Table 3:

Table 3
Final pH Values for Different HRT Variations

HRT	Initial pH	Final pH
7	7,68	7,5
14		7,2
21		7

Table 3 shows that the final pH of the waste after fermentation did not show a significant increase. This aligns with the literature, which indicates that the optimal pH for methanogenesis is between 6.8 and 7.2, which is not far from the initial pH. Research by Baena *et al.*, (2022) confirms that the optimal pH for methanogenesis ranges from 6.6 to 7.5, with an ideal pH around 7.0. Maintaining this pH range ensures an optimal environment for microbial activity, which is crucial for efficient anaerobic fermentation and biogas production.

The OLR values are calculated by dividing the COD of the sample by the HRT. The OLR values are obtained from the HRT of the Tofu Wastewater samples from the Tofu Industry.

Table 4
OLR Values for Different HRT Variations

COD(Kg/m^3)	HRT(Days)	OLR(Kg/m^3/day)
38,38	7	5,482
	14	2,741
	21	1,827

The OLR values decrease with each increase in HRT, indicating that a higher HRT results in a lower OLR. Research shows that variations in OLR and HRT significantly impact the performance of anaerobic digesters. According to Saranadagoudar, Mise and Kori, (2022), increasing HRT leads to a significant reduction in OLR, improving organic material degradation's stability and efficiency. This is consistent with the literature, which indicates that higher HRT values correspond to lower OLR values.

The HRT value affects the amount of biogas produced; a higher HRT results in greater production. In the experiments, an optimal HRT of 14 days was achieved. Previous studies have shown that the impact of HRT on biogas production is significant. Research by Bi *et al.*, (2020) demonstrates that at higher HRTs, biogas production and organic degradation efficiency are more optimal. Additionally, Blasco-Gómez *et al.*, (2017) indicated that extending the HRT can substantially increase methane production, showing a positive correlation between increased HRT and higher biogas production. Further research by Li *et al.*, (2021) supports these findings, highlighting that optimizing HRT is crucial for achieving maximum biogas production in anaerobic digestion systems, especially when using various substrates such as cow manure and food waste.

Results of the gas composition analysis for the HRT 21-day variable are presented in Table 5:

Table 5
Biogas Composition for HRT 21 Days

Composition	Concentration
Methane	2,47 %
Carbon Dioxide	0,22 %
Air	97 %

Table 5 shows that the biogas produced under the HRT 21-day variable does not meet the literature standard for methane content, which is 50-75% (Handbook, 2008).

The analysis of methane content in biogas is essential to determine the percentage of methane in the biogas. The results from the Energy Laboratory at the ITS Robotics Center using Gas Chromatography indicate a biogas composition of 2.47% methane, 0.22% carbon dioxide, and 97% air. Surendra *et al.*, (2015) reported that biogas from anaerobic digesters typically contains 50-75% methane and 25-50% carbon dioxide, with trace amounts of other gases. Variations in biogas composition can be due to various factors. Research by Zhang *et al.*, (2014) demonstrated that substrate type, reactor operational conditions, and processing methods can influence the final biogas composition. They found that optimizing parameters such as temperature, pH, and hydraulic retention time could enhance methane production by up to 80%.

The Effect of Hydraulic Retention Time (HRT) on Biogas Production

The retention time of waste significantly influences the degradation reaction by bacteria. The longer the waste retention time, the more organic particles are degraded by microorganisms in the reactor, which affects biogas production. Thus, the more organic particles are decomposed, the greater the biogas production (Rambe, Iriany and Irvan, 2014). Recent research indicates that increased retention time can enhance methane production. For instance, a study by Kim, Lee and Yoon, (2024) found that using magnetite in anaerobic digesters can accelerate methane production rates by up to 56.6%, with significantly shorter retention times compared to without the addition of magnetite.

The Effect of HRT on Final pH Value After the Fermentation Process

At the beginning of anaerobic fermentation reactions, the pH value decreases as volatile fatty acids (VFA) or volatile fatty acids are produced. The pH drop indicates the occurrence of acidification. Acidification is characterized by high acid concentrations due to the conversion of hydrolysis products into volatile fatty acids like acetate, propionate, and butyrate. During the methanogenesis stage, methane-forming bacteria consume VFAs, increasing alkalinity and raising the pH until a stable pH is achieved (Rambe, Iriany and Irvan, 2014). Recent research confirms that lower pH values enhance VFA production during anaerobic fermentation. Eregowda *et al.*, (2020) found that a pH drop to around 6.0-6.8 is highly beneficial for maintaining an efficient and stable microbial ecosystem, supporting higher VFA production. Additionally, Jiang *et al.*, (2013) research shows that the optimal pH for VFA production from food waste ranges from 5.5 to 7.0. At this pH, VFA concentrations reach their peak, supporting further acidogenesis.

The Effect of OLR on Gas Production

Organic Loading Rate (OLR) is a crucial parameter as it indicates the daily amount of volatile solids fed into the digester. Volatile solids primarily consist of processed organic material, while the remainder are non-processable. Recent research shows that increasing OLR can enhance biogas production up to a certain limit. For example, Ahlberg-Eliasson *et al.*, (2021) found that biogas plants using liquid cattle manure typically operate at OLRs of 2–5 kg VS/m³ per day. Other studies indicate that increasing OLR can improve methane yields and degradation efficiency, especially under thermophilic conditions, which allow higher organic loading without altering hydraulic retention time (Mata-Alvarez *et al.*, 2014). However, it is essential to consider the risk of volatile fatty acid accumulation, which can inhibit methanogenic activity at very high OLRs (Lehtomäki, Viinikainen and Rintala, 2008).

CONCLUSION

The average gas production is 393.57 mL with an HRT of 7 days, 472.14 mL with an HRT of 14 days, and 204.04 mL with an HRT of 21 days. The optimal gas production was achieved with an HRT of 14 days. The operational conditions are consistent with the literature, with a temperature of 30°C and final pH values of 7.5, 7.2, and 7. The gas composition comprises 2.47% methane, 0.22% carbon dioxide, and 97% air.

SUGGESTION

Various reactor designs such as UASB, CSTR, and plug flow reactors are recommended for future research. Operational conditions, particularly reactor pressure, should be carefully monitored to facilitate more accessible gas release. For HRTs of 7 and 14 days, experiments should be conducted for at least 20-30 days to achieve steady-state gas results.

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