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"The Impact of Self-Agitating Anaerobic Batch Digester Design on Biogas Production of Cattle Manure Co-Digested with *Lemna minor*"

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ABSTRACT: The continuation of utilizing fossil fuels as cooking energy sources in rural communities in the Philippines causes more citizens to be at risk of developing numerous health illnesses. This study aimed to propose a potential solution to this problem by innovating a self-agitating anaerobic batch digester, promoting biogas production of cattle manure co-digested with *Lemna minor*. Two anaerobic batch digester designs, one with baffles and one without, were observed within 22 days to determine the impact of the anaerobic digester design on mixing and biogas production yield. The study contained two pairs of anaerobic batch digesters, the initial and improved digester. The water displacement method was used to measure the biogas yield from the initial and improved digesters. The results of this study on the quantity of biogas produced between the initial experimental designs measured every six days and revised experimental designs measured every four days concluded that anaerobic batch digester designs with baffles produced a superior amount of biogas with 5468.88 cm^3 more yield than the digester without baffles. Utilizing an Independent Sample T-test, the difference in biogas production is considered significant, ($p = .174$). Similar studies in the future are encouraged to explore variations in the anaerobic digester design outside of the placement of baffles, including factors such as the materials used and the period of observation due to the limitations of this study.

KEYWORDS: anaerobic digestion; biogas; cattle manure; co-digestion; *Lemna minor*

INTRODUCTION

Air pollution has become a major contributor to the continuous deterioration of the environment (World Health Organization [WHO], 2018). After having the third highest fatality rate due to outdoor air pollution after China and Mongolia in the world, it is important to innovate our source of energy in the Philippines, (WHO, 2018). Creating a sustainable and renewable energy source with lessened effects on the environment and health is this study's focus. It promotes help in a community that primarily uses woodfires and are subjected to harmful air emissions. In Sitio Makabuhay, Brgy. Poblacion, Muntinlupa City, the families living there are below the poverty line and do not have access to biogas. Sitio Makabuhay is also dominated by females and children meaning the research had to consider how emissions weigh more towards children as they consume in proportion to their bodies (United States Environmental Protection Agency [US EPA], 2015). This means that the children and people there are more at risk of attaining respiratory and cardiovascular problems (Huxham & Jung, 2019). The study went through with learning about the batch digester using cattle manure with *Lemna minor* and its biogas production while considering how rural areas have little to no access to cost and energy. Anaerobic digesters are systems in which biomass is broken down by anaerobic bacteria to form methane gas for cooking. In batch systems, the feedstock is only added to the digester at the beginning of the digestion process. This type of feeding is preferred for its simplicity which reduces the necessary material cost of the digester. Mixing itself plays an important factor in the contribution of biogas yield as it increases production compared to no mixing (Wang et al., 2021). However, it does consume electricity. Therefore, the digester was considered as a self-agitating anaerobic digester design that did not require mixing and would be adjusted to better suit rural conditions. A case study on a digester using cattle manure co-digested with *Lemna minor* has not been conducted before and as such, the objective of this study was to further enhance the biogas production along with cost and energy through a self-agitating anaerobic digester.

This paper considered factors such as mixing and its intensity towards the overall production of the design. To add, the research found differences between biogas production in certain time frames and the differences between the initial and improved batch digester designs. The difference between both designs was in its yield. The study itself was limited to the usage of cow dung with *Lemnar minor* as a feedstock as a safer and more accessible substitute (Norton, n.d.) and therefore did not center towards other feedstocks. Presenting the comparisons with different batch designs, the study showed results discussed yield and efficiency of each made digester. As such, the study showed how mixing with the substrate of cattle manure and *Lemna minor* affected the biogas production in a way that the digester design stays sustainable, accessible, and cost-effective. However, the study still lacks an understanding of some areas of the digester. Since we limited our feedstock into two, the addition of other substrates may cause other reactions and yields which will need to be studied upon. To add, the design of this digester will resemble other digesters such as the ones of Qi et al. (2013) and Jegede et al. (2019b). Despite the similarities, this research still created a self-agitating anaerobic digester that optimized yield, cost, and energy.

METHODOLOGY

Research Design

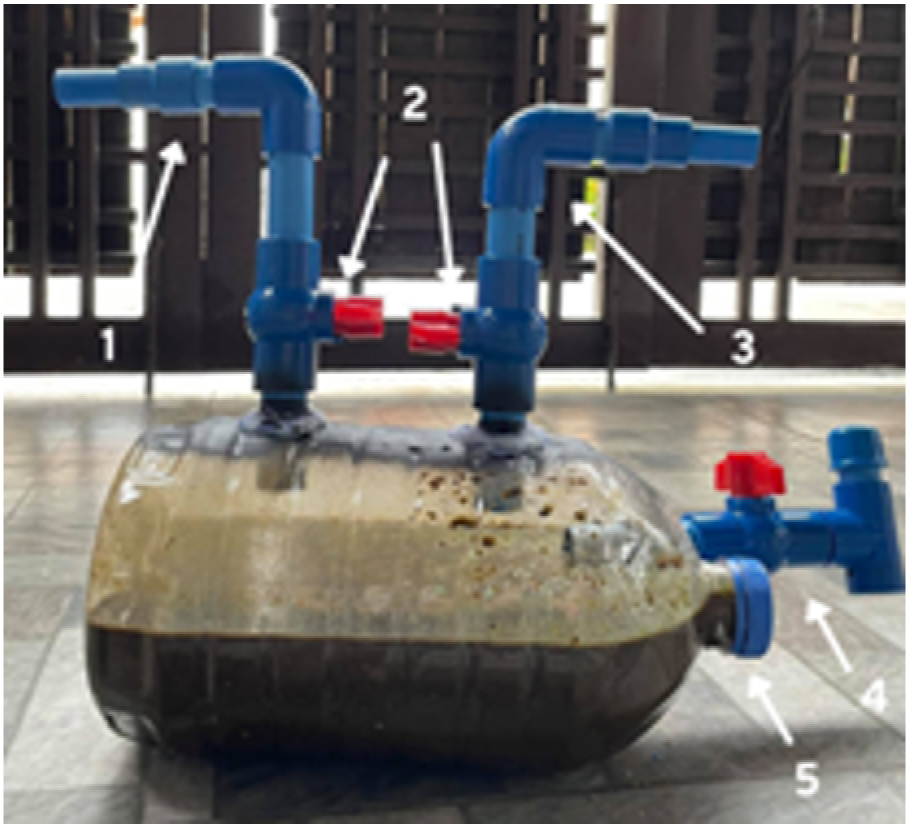
The research used an experimental setup. Two proposed designs of an anaerobic batch digester were varied to determine the impact of its design on biogas production yield. In the experiment, quantitative data on the amount of biogas were recorded.

Experimental Setup

The researchers considered 2 proposed pairs of anaerobic batch digester designs, the initial and improved digester, to distinguish the effects of anaerobic digester design on biogas production.

Figure 1.1

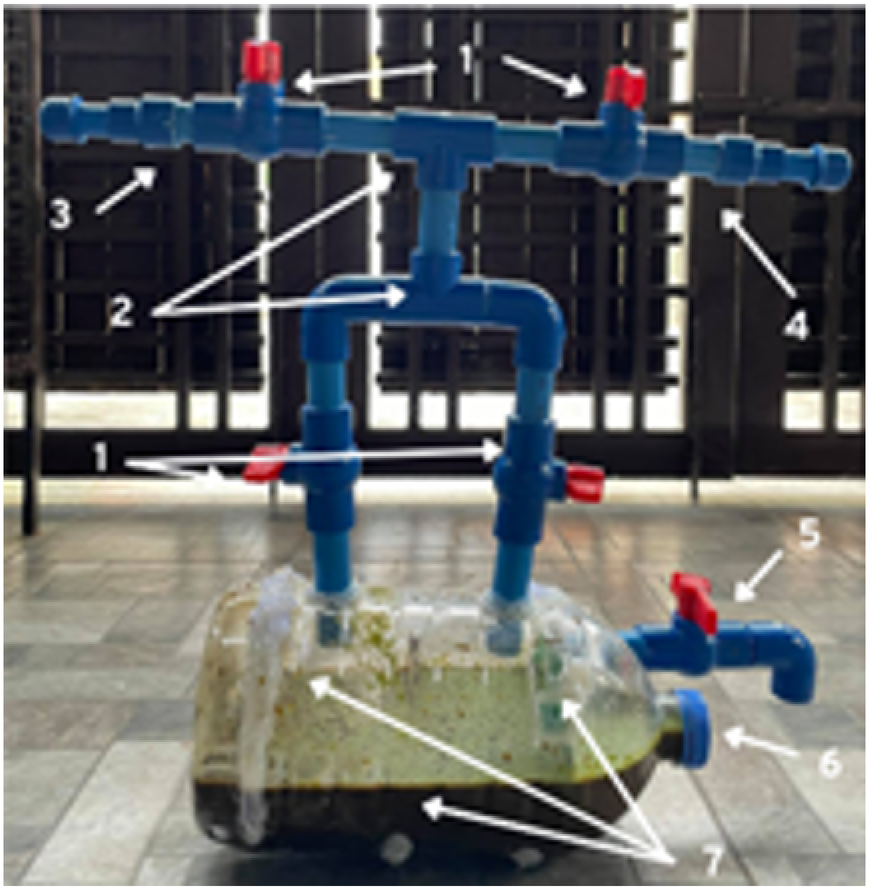
Initial Anaerobic Batch Digester Design without Baffles



Note: 1 - Manometer Tube; 2 - Valves; 3 - Water Displacement Tube; 4 - Effluent Outlet; 5 - Influent Inlet

Figure 1.2

Initial Anaerobic Batch Digester Design without Baffles



Notes: 1 - Valves; 2 - Three-way Connector; 3 - Manometer Tube; 4 - Water Displacement Tube; 5 - Effluent Outlet; 6 - Influent Inlet; 7 – Baffles

To elaborate on the setup of the initial digester, an anaerobic batch digester requires an influent inlet, effluent outlet, and baffles for the digester with baffles, as seen in figures 1.1 and 1.2. Both initial batch digesters have the capacity for 6 liters (L).

Figure 2.1

Improved Anaerobic Batch Digester Design without Baffles

Note: 1 - Influent Inlet 2 - Water Displacement Tube 3 - Valve 4 - Effluent Outlet

Figure 2.2

Improved Anaerobic Batch Digester Design with Baffles

Note: 1 - Influent Inlet 2 - Water Displacement Tube 3 - Valve 4 - Effluent Outlet 5 – Baffle

As seen in figures 2.1 and 2.2, the setup of the improved anaerobic batch digester requires the same inlets and outlets, but the difference is the materials used and the capacity for storage that is 6.6 liters (L).

The presented design is a single-stage digester that is focused on effectively using the potential of biogas through less energy, financial cost, and cattle manure resources and reducing the dependence on fossil fuels.

Research Locale and Samples

The study was conducted on the private property of one of the researchers located in Bacoor City in the Philippines to prevent the researchers from being exposed to the COVID-19 virus. The data was collected in an open space to reduce the risk of the bacteria spreading infections to the people residing in the building and help protect the indoor air quality of the building from being affected by potential gas leaks from the digester.

The temperature in the researcher's location ranged from 23ºC - 34ºC during the experimentation (The Weather Channel, n.d.). This means that the temperature was in Mesophilic conditions which are ideal to produce biogas.

Samples of cow manure were collected in the streets and grass fields in Bacoor City near the location where the experiment was conducted. *Lemna minor* samples were obtained from a local seller in the region via an e-commerce website. Safety protocols were strictly always followed during the collection of these samples.

Materials

Table 1

Data Gathering Procedure Materials

Initial Design	Improved Design
Body of the Anaerobic Digester	
6-liter (L) PET bottles, aluminum cans (baffles), super glues, glue gun sticks, small hacksaw, ¾ & ½ PVC pipes, ¾ PVC pipe valves, ¾ three-way PVC connectors, ¾ PVC pipe elbow, ¾ & ½ PVC pipe connecter end plugs, ½ PVC pipe reducer and ½ clear & flexible tube	6.6-liter (L) PET bottles, ¾ clear & flexible tube, ½ LPG hose, ½ LPG hose clamps, and ½ LPG hose connectors
Substrates	
3-liters (L) Cattle Manure & 0.30-liter (L) *Lemna Minor*	4.5-liters (L) Cattle Manure & 0.45-liter (L) *Lemna Minor*

Instruments	
homemade manometer -- ½ clear & flexible tubes, plywood, food coloring, ruler, tape, PVC tube fasteners, and GI clamps	water displacement method -- ½ clear & flexible tubes, cylindrical container, and small basin
water displacement method -- ¾ & ½ PVC pipes, ½ clear & flexible tubes, ¾ PVC pipe connecter end plugs	

Instruments

Figure 3

Homemade Manometer

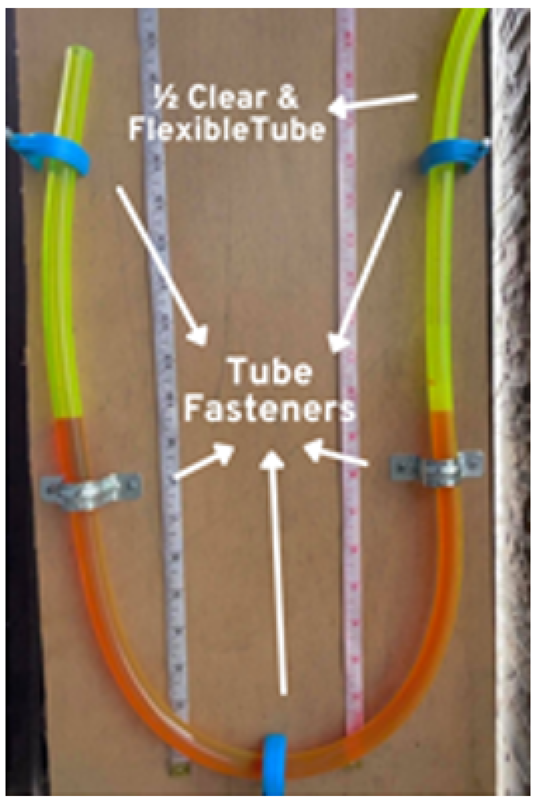


Figure 4

Water Displacement inspired by Tira et al. (2019)

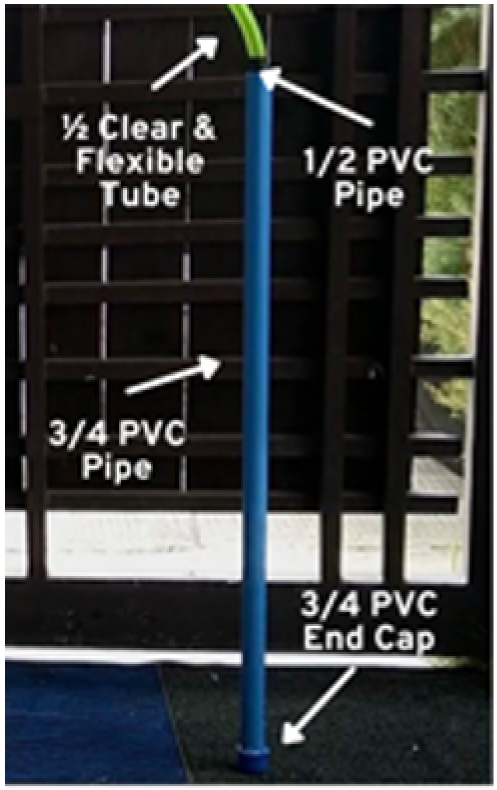


Figure 5

Water Displacement Method used for Improved Anaerobic Digester

For the initial anaerobic batch digesters, two instruments were used, which are a homemade manometer and a water displacement tube. To measure pressure, researchers made their own manometer--thus, the following materials shown in Table 1 were needed.

The water displacement method inspired by Tira et al. (2019) was used to measure the biogas yield from the initial digesters, whereas the improved digesters used a cylindrical container and a small basin.

Data Gathering Procedure

Pre-experimentation

Before conducting the research methods, a research ethics checklist and request letter for data gathering were accomplished and submitted to their research adviser. The researchers also consulted with a chemical engineering graduate for guidance and suggestions and asked advice from biology and physics teachers. The materials shown in Table 1 were purchased from a hardware shop in Bacoor, Cavite. All the materials were bought by a fully vaccinated adult, following all the safety precautions. Furthermore, the money needed to purchase these materials was sent online using mobile wallet apps.

Organic Substrate Collection and Preparation

The researchers obtained cattle manure from an open lot near the house of one of the researchers in Bacoor, Cavite. Moreover, the researchers chose *Lemna minor* to be co-digested with cattle manure, which was bought from Shopee, an e-commerce platform.

During experimentation

The data gathering procedure was conducted in a month which started on August 06, 2021, and ended on September 10, 2021. In consideration of the safety of the researchers, safety precautions were always observed and were performed under the supervision of an adult leader. After acquiring three liters (L) of cattle manure and one batch of 1.5L of *Lemna minor*, the substrates were mixed and kept in two anaerobic batch digesters in a researcher's house at an optimal mesophilic temperature. The two initial anaerobic digesters were left untouched until every day that falls on a multiple of three (e.g., third & sixth day) for a total of 6 days to measure pressure and biogas yield. On the other hand, the improved digesters were measured and left untouched until every day that fell on a multiple of four (e.g fourth, sixth, twelfth day) to measure only the biogas yield. The instruments used to measure pressure and biogas yield of the initial digester were a homemade manometer and water displacement tube, respectively, as shown in Figures 3 and 4. Moreover, the instrument used to measure the biogas yield from the improved digester was a cylindrical container and a small basin, as presented in Figure 5.

Phase 1: Using the Initial Anaerobic Batch Digester Design

The two initial anaerobic digesters were made identical in function and construction except for one feature--baffles, as seen in Figures 1.1 and 1.2. The baffles present in one digester (and absent in the other) refer to three dividers that split the space into four compartments. The initial anaerobic digesters were then put in one place in the researchers' house in a prostate position.

Table 2

Initial Anaerobic Digester Construction

Steps and Description	Without Baffles	With Baffles
1. Cut all the materials needed 2. Assemble and glue the cut materials with plastic glue and PVC pipe cement. Ensure that there will be no sources of gas leaks. 3. Insert the assembled materials into the 6-liter PET Bottle using glue guns and sticks. 4. Mix cattle manure with *Lemna minor* and water, put it inside the initial anaerobic digester, and leave for a few days.	- ¾ PVC Pipe: (3 pcs.) 8 cm, (2 pcs.) 4 cm, and (3 pcs.) 2 cm - ½ PVC Pipe: (2 pcs.) 2 cm - 6-liter PET Bottle: (3 holes for ¾ PVC pipes) 1.905 cm - 1.5-liter of cattle manure - 0.15-liter *Lemna minor* - 1.35-liter water	- ¾ PVC Pipe: (4 pcs.) 8 cm, (4 pcs.) 4 cm, and (4 pcs.) 2 cm - ½ PVC Pipe: (2 pcs.) 2 cm - Aluminum Can: (3 pcs.) 19 cm - 6-liter PET Bottle: (3 holes for ¾ PVC pipes) 1.905 cm and (3 segments for the aluminum cans) 19 cm - 1.5-liter of cattle manure - 0.15-liter *Lemna minor* - 1.35-liter water

Table 2 shows the construction of both initial anaerobic digesters, without and with baffles, which is inspired by Qi et al.'s (2013) self-agitating digester design.

Phase 2: Using the Improved Anaerobic Batch Digester Design

On account of reasons, revisions were made to the anaerobic digester designs in hopes for an improvement in outcome. Due to time constraints, the researchers decided to alter multiple aspects in digester design and measurement methodologies. A summary of the revisions can be seen in tables 3.1 and 3.2

Table 3.1

Summary of key digester design revisions

	Initial Design	**Improved Design**
Digester Body	6.0 Liter PET Bottle	6.6 Liter PET Bottle
Body Opacity	Transparent	Opaque (Painted Black)
Gas Transportation	PVC Valve & Pipes	LPG Valve & Hoses and Plastic Tubing
Baffles	2 Upper & 1 Lower	1 Lower
Position	Prostate (Horizontal)	Upright (Vertical)

Table 3.2

Summary of key data collection revision

	Initial Design	**Improved Design**
Pressure	Measured	Excluded
Water Displacement Method	Gas Enters Above Tube	Gas Enters Below Tube
Data Collection Interval	3 Days	4 Days
Experiment Duration	6 Days	16 Days

Table 4

Improved Anaerobic Digester Construction

Steps and Description	Without Baffles	With Baffles
1. Cut all the materials needed 2. Assemble and glue the cut materials with plastic glue and PVC pipe cement. Ensure that there will be no sources of gas leaks. 3. Insert the assembled materials into the 6-liter PET Bottle using glue guns and sticks. 4. Mix cattle manure with *Lemna minor* and water, put it inside the improved anaerobic digester.. 5. Paint the body of the improved anaerobic digester with black paint, and leave for a few days.	- ½ LPG hose: (2 pcs.) 6.35 cm and (1 pc.) 3.81 cm - 6.6-liter PET Bottle: (2 holes for ½ LPG hose) 1.27 cm - 2.25-liter of cattle manure - 0.225-liter *Lemna minor* - 2.025-liter water	- ½ LPG hose: (2 pcs.) 6.35 cm and (1 pc.) 3.81 cm - Aluminum Can: (1 pc.) 19 cm - 6.6-liter PET Bottle: (2 holes for ½ LPG hose) 1.27 cm and (1 segment for the aluminum cans) 19 cm - 2.25-liter of cattle manure - 0.225-liter *Lemna minor* - 2.025-liter water

Table 4 shows the step-by-step process of the creation of both improved anaerobic digesters without and with baffles, which is inspired by Jegede et al. 's (2019b) Optimized Chinese Dome Digester.

Post experimentation

In preparation for statistical treatment and analysis, the data collected (pressure and biogas yield) from both the initial and improved anaerobic digesters were arranged in a Microsoft Excel spreadsheet.

Data Analysis

The collected data were analyzed using descriptive analysis and an independent t-test with the aid of IBM SPSS Software version 26. Descriptive analysis was used to determine the amount of biogas yield every 3 days, for the initial digester, and 4 days for the improved digester. It was also used to compare the yield from both anaerobic digesters. Moreover, an Independent T-test was used to determine the difference of the biogas production. It also allowed the researchers to compare the means of the data gathered from the improved anaerobic batch digester design after 16 days, and determine the gap result of biogas yield by both the improved design of the digester with and without baffles.

RESULTS AND DISCUSSION

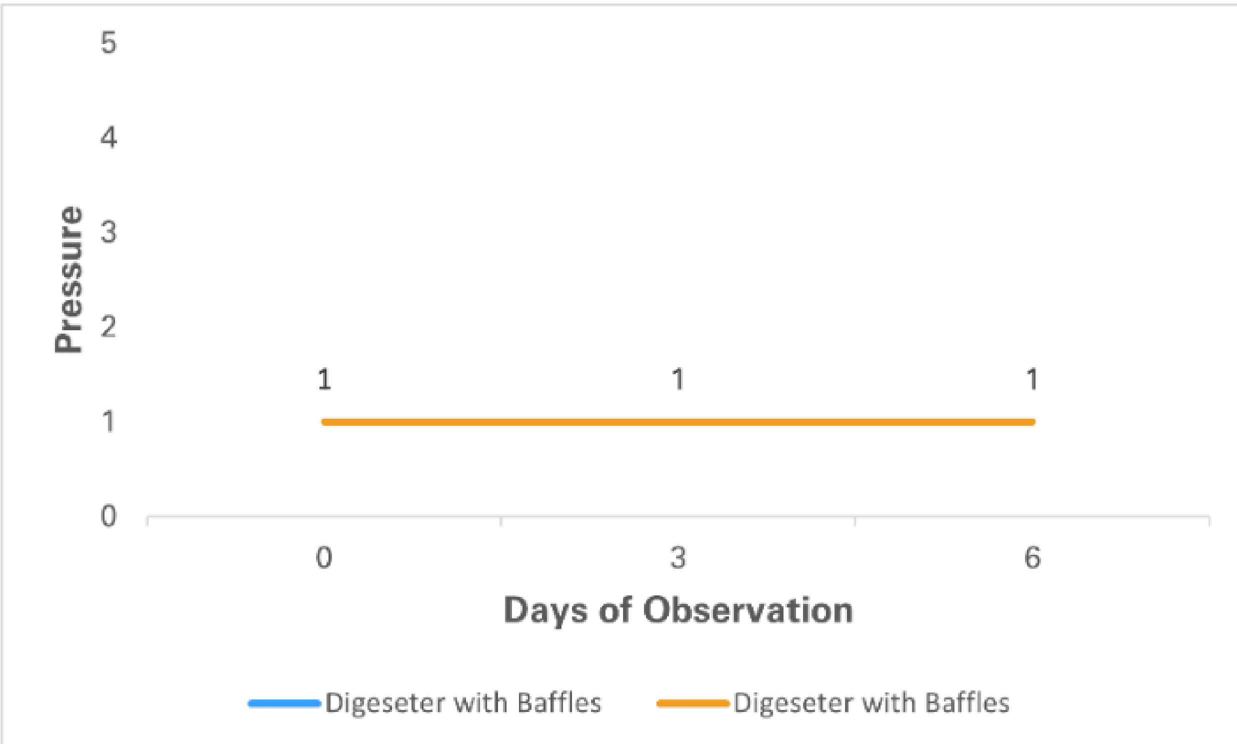
To compare the biogas yields of the constructed anaerobic digesters, both descriptive and independent t-test were used to analyze the data from the digesters.

The setup of the initial digester both with and without baffles consisted of an influent inlet, effluent outlet, and baffles for the digester with baffles. Both initial batch digesters can store 6 liters (L) of the substrate. On the contrary, the setup of the improved anaerobic batch digester consisted of the same inlets and outlets, however, the materials used for the overall digester aside from the inlets and outlets are different and the main body can store 6.6 liters (L) of the substrate. The inlets and outlets help insert and let out the substrate and biogas produced from the main body while the baffles aid in the mixing process of the substrate. There was no difference in biogas yield between the digesters with and without baffles in the initial design. The initial design did not produce a significant amount of biogas. After redesigning the digester and modifying elements impacting biogas production, it exhibited an improvement in generating biogas output after 16 days. The improved digester with baffles, in fact, generated an average of 418.46 cm^3 per day.

In this study, biogas production was evaluated by the volume (cm^3) of gas collected. It was observed that both the initial digesters had produced a total of 0 cm^3 of biogas over the 6-day course of experimentation. Gas volume was measured via the water displacement method wherein the amount of water displaced in the displacement tube is equivalent to the amount of gas collected.

Figure 6

Pressure every 3 days for 6 days



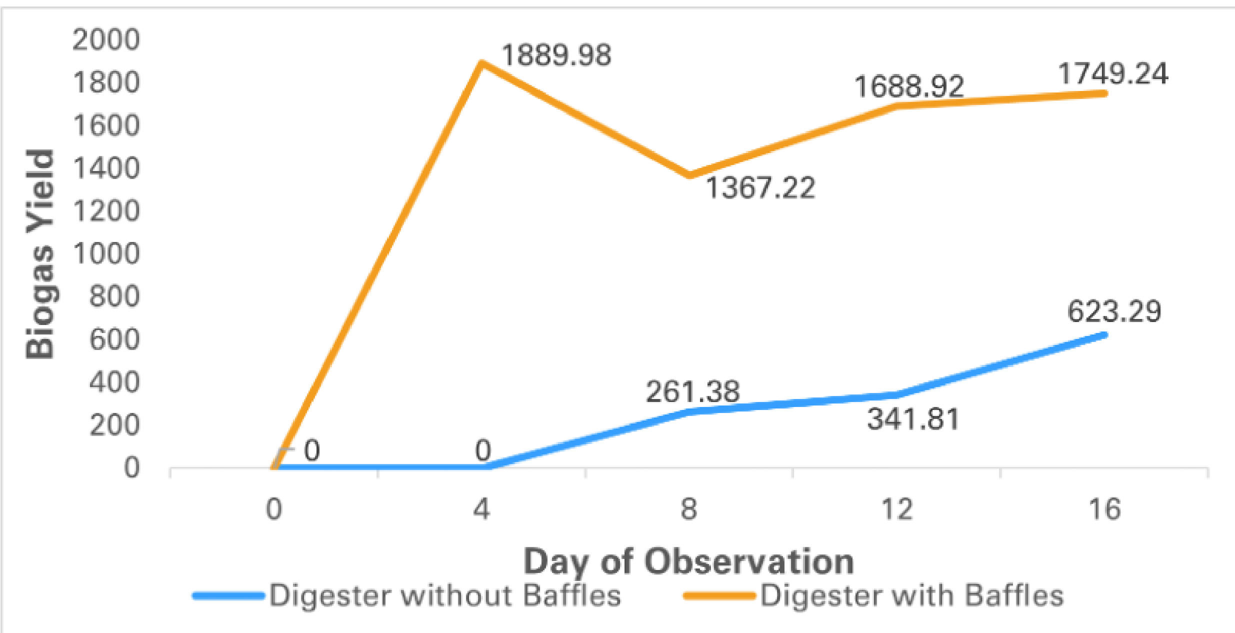
To support the accuracy of the water displacement method, the pressure (atm) inside each digesting chamber was measured before each instance of volume measurement via a homemade open-end manometer. As presented in Figure 6, the pressure inside the digesters was at a constant of 1 atm which is equivalent to atmospheric pressure indicating no variation of pressure throughout the experimentation period.

As mentioned previously, the data gathered from the experiment conducted with the initial digester designs indicated no signs of biogas production within the 6-day timeframe. Due to this being true to both the digester with and without baffles, it is implied that there is no difference in the overall biogas produced by both digesters after 6 days. Originally, the data gathered from both digesters would have been subjected to comparison via independent t-tests. However, with the data recorded from both digesters being at a constant of 0 cm³, it is nonessential to use statistical analysis to determine the significant difference between the two groups.

In consideration of the aforementioned results regarding the measurements of biogas yield and pressure, the researchers opted to improve the anaerobic digester designs with the aspiration to produce positive results. In addition, the measurement of pressure was no longer conducted to minimize any error that may have occurred due to it. The following sections will discuss the results of the improved digester designs with regard to biogas production.

Figure 7

Biogas Yield every 4 days for 16 days



Due to the fact that the two initial anaerobic digester designs failed to produce any amount of biogas, the researchers decided to create new and improved designs which the researchers then experimented with. The improved designs, as seen in Figure 2.1b and 2.2b, are seen to be better designs in terms of gas production as observed in Figures 6 and 8. The improved digesters were measured every four days.

As seen in Figure 7, the gas yield of the improved digester was recorded to be the highest at Day 4 spiking at 1889.98 cm^3. At Day 8, the digester then produced less gas relative to its Day 4 yield. The digester with baffles then had progressively increased yields during the remaining days. In contrast, the improved digester without baffles produced no biogas during the first four days. However, at Day 8 the digester produced 261.38 cm^3 of biogas with its recorded yield increasing after each observation reaching 623.29 cm^3 at Day 16.

To summarize, the improved digester with baffles produced a total of 6695.36 cm^3 while the digester without baffles produced a total of 1226.48 cm^3 during the 16-day experiment. In total, the digester with baffles produced 5468.88 cm^3 more than the digester without baffles. Further analysis showed that the digester with baffles produced an average of 418.46 cm^3 per day. The digester without baffles, on the other hand, produced an average of 76.655 cm^3 per day.

Table 5

Independent Sample Test Result

		Levene's Test for Equality of Variances		**t-test for Equality of Means**					
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Biogas	Equal variances assumed	2.228	.174	-2.999	8	.017	-1093.78	-1934.89	-252.66
	Equal variances not assumed			-2.999	4.902	.031	-1093.78	-2037.05	-150.50

Table 5 presents the Independent Test result which indicates a significant difference in the biogas yield of the digesters, following the improved designs, with baffles, and without baffles after 16 days. The p-value reported for Levene's Test for Equality of Variance ($p = .174$) is greater than 0.05, indicating that the variability in the two conditions is not significantly different; the two variances are approximately equal. Given this condition, the "Equal variances assumed" row must be analyzed for the t-test (and corresponding confidence interval) result.

The negative t-value ($t(8) = -2.999$) implies that the first group, digester without baffles, is significantly lower than the mean of the second group, digester with baffles. Moreover, the Sig. (2-Tailed) value ($p = 0.017$) is less than 0.05 (p-value < 0.05) further suggests that there is a significant difference in biogas production mean of the digester without baffles and with baffles.

Discussion

Factors Affecting Biogas Production of Initial Anaerobic Batch Digester Design

As the reliance on kerosene, coal or wood-fueled stoves further increases in rural communities in the Philippines due to their cost and availability (Remedio, 2010), this study seeks to establish the effectiveness of innovative anaerobic digester designs. Thus, the first stage of the data analysis serves to determine the amount of biogas produced by the anaerobic digesters, following the initial designs every 3 days. The analysis exhibits no presence of biogas production from both initial anaerobic digesters, with and without baffles. The pressure also shows no variation, as it remained constant at 1 atm. These results might have happened due to several instances concerning the design of the digester, temperature, pH value, retention time, and measurement, as these are some of the significant factors of optimizing anaerobic digestion (Dana, 2010; Meegoda et al., 2018; Mir, Hussain, & Verma, 2016).

The initial anaerobic digester designs were inspired by the Self-Agitating Anaerobic Digester of Qi et al. (2013). The primary difference of the initial digester design was the absence of the U-tube and the presence of a gas outlet in chamber A. With that, the removal of the U-tube possibly affected gas production as it immensely affects mixing and aids in self agitation, which can then result in higher biogas production (Qi et al., 2013; Wang et al., 2021).

The design also specifies several cuts to the anaerobic digesters for the attachment of the influent inlet, effluent outlet, manometer tube, water displacement tube, and baffles into the bottles. These dissections could also be one of the reasons for the digesters not having to produce biogas, as several cuts could result in possible gas leakage.

According to Mir, Hussain, and Verma (2016), operating temperature is vital in the performance of anaerobic digestion as it permits optimum biogas production. The compulsory temperature for anaerobic digestion to fully perform is mesophilic (25–40ºC) and thermophilic (50–65ºC). However, due to inevitable circumstances, including instantaneous weather changes, the temperature throughout the 6-day duration fluctuated. With that, the proposed temperature for efficient methane production was uncontrolled. Moreover, anaerobic digesters are temperature-sensitive, and as the temperature spiked from a certain degree due to weather changes, a fall in biogas production happens (Cioabla et al., 2012; Mir et al., 2016). It also results in the disruption of microbial activity, which then affects the operation of the anaerobic digestion (Wang et al., 2019). For this reason, the frequent changes in the temperature may have contributed to zero biogas yield since failure to regulate and control the temperature leads to problems with the production of biogas (Dana, 2010).

Along with temperature, the acidity or pH level of the organic waste is a vital factor to the digesters' ability to produce biogas (Dana, 2010). The performance of a digester is most effective near the neutral point, up to a pH of about 8.5. However, as the pH value fluctuates during the stages of anaerobic digestion, it is necessary to maintain a constant pH within a range of pH 6.8 to 8.5 at the beginning of the digestion (Mir et al., 2016; Zhang et al., 2011). Thus, the pH level of the feedstock is a potential prospect in the lack of biogas production as it may not have been within the ideal range. A pH level not within the optimal range (pH 6.8 - 8.5) would result in acid accumulation and digester malfunction (Kang & Yuan, 2016). Furthermore, the acidic environment in which growth and gas production is inhabited influences the methanogenic bacteria, which may hinder biogas production (Mir et al., 2016). Hence, the effect of the acidic environment may be an additional prospect in the lack of biogas production.

The consummate retention time for finished anaerobic digestion is 12–24 days, thermophilic, and 15–30 days, mesophilic (Mir et al., 2016). In this study, the duration of the entire experimentation with the initial anaerobic digester designs was only 6 days. The time duration of the substrates inside the digesters is one of the most significant factors when optimizing biogas as it enables the digester to produce a higher biogas yield (Chein & Neibling, 2014). It is then put into consideration that the shortened duration of the experiment on the initial digesters could have contributed to the result of no biogas observed due to it not reaching near the average retention time.

It should also be highly considered that the noted gas production failure may be attributed to the inaccurate measuring devices or their misuse (Parajuli, 2011). Giving emphasis to the fact that the measuring devices were made from scratch, factors such as human error could have played a part in causing the homemade manometer and water displacement tube to give inaccurate readings. It is also plausible that the researchers' inexperience on using the instruments, most especially the water displacement method inspired by Tira et al. (2019), have caused the instruments to be used incorrectly, thus not being able to give off a proper reading. Although, there is a low chance that the main error lies within the water displacement method as the U-shaped manometer was first used before each observation of biogas yield to make sure that the water displacement method gives accurate results via the comparison of pressure and yield. The pressure however showed a consistency of no change thus encouraging that the error lies before the measurement of gas yield.

Enhancement of the Anaerobic Batch Digester Design

In view of the first set of digesters having been observed to not produce any biogas, the anaerobic batch digester design was improved by the researchers. Similarly, to the initial design, the improved design made use of a PET bottle to act as the digester body. The key difference between the two is the bottle dimensions and position. The size of the bottle has been upscaled to 6.6 liters (L), in contrast to 6.0 L, mainly due to its increased load capacity, availability, and suitability for tinkering. In particular, the digester body has enough space for the addition of an influent inlet, effluent outlet, and baffle. The digester was positioned upright to replicate a Chinese Dome Digester (CDD) in which the upper portion of the bottle acts as a dome due to its hemispherical shape. This improves the structural strength of the digester making it more resistant to high pressures while also aiding the biogas to flow towards the outlet due to its funnel-like shape (Jegede et al., 2012).

Dissimilar to the Qi et al.'s (2013) Self-Agitation Anaerobic Baffled Reactor (SA-ABR) and Jegede et al.'s (2019) Optimized Chinese Dome Digester, the improved digester design only featured one lower baffle to aid in the process of mixing. One of the reasons is due the upright position of the digester reducing its horizontal space which may cause implications when multiple baffles are added. Additionally, another important motive was to reduce the risk of potential gas leaks during experimentation. During the construction of the digester, cuts are made on the bottle to make way for the insertion of baffles. The more dissections made to the digester, the higher the chances for an unaccounted error, such as gas leaks, to occur (Rauf, 2015b). The upper baffles which are included in most self-agitating anaerobic designs were removed to potentially contribute in preventing this issue from occurring. Although upper baffles play an essential role in mixing, they also separate the biogas and only allow one chamber to be collected at once for mixing efficiency to be achieved (Jegede et al., 2019; Qi et al., 2013). This makes it difficult to measure the total biogas amount in the digester.

Furthermore, the anaerobic digester bodies were painted black as to improve thermal insulation (Rauf, 2015b). It is also worth mentioning that the valves and pipes were switched from PVC to LPG valves & hoses and flexible plastic tubing to better suit gas transportation.

Three primary revisions were also made to the data collection namely in pressure measurements, collection intervals, and the water displacement methodology. Pressure was initially measured to verify the water displacement method; however it was excluded to again reduce the chances of gas escaping (Lenkiewicz & Webster, 2017) since the gas would then be able to flow directly to the water displacement tube. Collection intervals were increased to four days, from three, to allow the gas amount to build up. Finally, the water displacement tube used in the initial version which was inspired by the design of Tira et al

(2019) was changed to the design based on traditional methods of water displacement (Selvankumar et al., 2017).

Biogas Production of Improved Anaerobic Digesters

Given the constraint of time in this research, numerous revisions were made to the anaerobic digester design. This led to the difficulty of determining the exact reason as to why the first batch of digesters produced no biogas. With more time given, fewer alterations would have been opted by the researchers to be able to find the factors that caused the initial anaerobic digesters to have failed in producing gas.

In contrast to the first set of anaerobic digesters, the improved anaerobic digester made with a baffle produced a relatively large amount of biogas. As seen in figure 6 (p. 17), there was a huge spike in the biogas yield of the improved baffled digester from Days 0 to 4. Meanwhile the digester without baffles remained at zero biogas produced. A possible reason for this is the failure of the container to be airtight (Rauf, 2015a). In the initial design, the bottle was in a horizontal position and the mixture may have put pressure on the cap, causing the cap to loosen. The hemispherical top of the improved digesters is said to provide structural strength, giving support against high pressures inside the digester (Jegede et al., 2019a; Rajendran et al., 2012). However, as seen in Figure 2.2 where the baffle is located, it was observed that even with the dome-like top of the improved baffled digester, there was a puncture at its base on Day 4 which was sealed when spotted. This puncture was caused by the immense amount of gas produced significantly increasing the pressure inside the digestion chamber. Since the puncture was located at the base of the digester, only a small amount of slurry exited the digester while all biogas remained.

On Day 8, biogas amount produced by the baffled digster was recorded to be 27.66% less than the yield on Day 4. A notable reason for this occurrence is the high pressure caused by gas production inside the digester between Days 4 and 8 causing a rupture in the top half of the digester. Specifically, it was located in the place where the baffle was inserted. It is hypothesized that the cooled glue sealing the baffle in place was not strong enough to resist the high pressure of the gas, thus causing the decrease in biogas amount recorded via the water displacement method. The seal was reinforced, and no other leaks were recorded on subsequent days. In spite of the data collection intervals being increased with the intention of aiding in the observation of gas yield, it can be concluded that it was counterproductive due to the pile up of gas causing problems in terms of pressure exceeding the desirable conditions.

The recorded biogas yield from Days 8 to 16 showed signs of stabilization. This is inferred from the slopes as presented in figure 6 (p. 17) to have relatively decreased in steepness. There was a notable difference in the gas production between the two digesters over the course of 16 days. The improved baffled digester never had a recorded biogas yield lower than 1367.22 cm^3 among the four observations collected. Meanwhile, the improved anaerobic digester with baffle never exceeded 623.29 cm^3 in a single observation. Although the differences are large, it is observed that the biogas production rate from the improved digester without baffles increased over time. This is most likely due to unbaffled digesters having more hydraulic retention time compared to digesters with baffles (Qi et al., 2013; Rajendran et al., 2012). Thus, it is likely that the unbaffled digester could have produced more biogas per day if the experimentation for the improved digesters exceeded 16 days. It is still however preferable to use baffled digesters due to their lower retention time, causing an overall increase in biogas production (Qi et al.i, 2013; Tilley et al., 2014).

The study developed a self-agitating anaerobic batch digester design, one with baffles and one without, while promoting the use of inexpensive and easily accessible materials (Pirelli et al., 2018). This is because self-agitating digesters release gas, which causes the pressure inside the digesting chamber to rise, forcing the slurry to move at random intervals with the help of baffles. Thus, mixing has an impact on quality and methane output. It also improves the interaction of microorganisms with the substrate, as well as the bacterial community's ability to get nutrients (Monnet, 2004). To emphasize, mixing is a crucial process that when maximized, can lead to abundant biogas production. To add, the necessity of mixing was mentioned in a study by Vögeli & Diener (2014), who claimed that mixing “blends raw material with digestate” and eliminates “temperature gradients in the digester” to prevent scum formation—a mass that can block pipes and foam the digester (p.

8-9). Furthermore, the inability to offer a mixing process, according to Hopfner-Sixt and Amon (2007), is one of the primary reasons for an anaerobic digester that does not generate an ideal outcome. With the claim of the importance of mixing, the early observations of the initial digester design produced no biogas yield. Due to this, the improved digester design was made similar to that of the Optimized Chinese Dome Digester (Jegede et al., 2019b). Through this change, mixing was maximized and produced a negative t-value ($t(8) = -2.999$) which demonstrated that the mean of the digester without baffles is considerably lower than the digester with baffles. Likewise, the fact that the (2-tailed) result ($p = 0.017$) is less than 0.05 (p-value 0.05) indicates that there is a significant difference in biogas output mean between the digester with and without baffles.

At the outset of the experimentation, there was not any observed difference in the biogas yield using the initial digester design with and without baffles. This was due to factors such as its materials, absence of a biogas outlet, inadequate storage capacity, absence of a U-tube, human error, and external environmental factors. However, after redesigning the digester and tweaking factors influencing the production of biogas, it showed an improvement in generating biogas yield after 16 days. Specifically, the digester with baffles produced an average of 418.46 cm^3 per day. The digester without baffles, on the other hand, produced an average of 76.655 cm^3 per day. The observations and interventions held an important role as it was considered to be able to acquire biogas after a certain amount of time.

CONCLUSIONS AND RECOMMENDATIONS

The study conducted on the effects of anaerobic batch digester design on biogas yield using cattle manure with *Lemna minor* as a co-digestor found a substantial difference in the biogas yield between the two digester designs due to the factor of mixing with and without baffles. With this, the study discovered fundamental findings that display the utilization of the anaerobic batch digester design through the following observations: (1) first, it was concluded that the initial designs of the anaerobic batch digesters produced zero biogas throughout the course of 6 days resulting in a total of 0.0 cm^3 of biogas production which was calculated using the water displacement method which showed that both the digester with and without baffles' overall biogas production after 6 days is just the same; (2) second, the study addressed the difference between the two digester designs with regard to the production of biogas yield. To illustrate, the digester with baffles generated 5468.88 cm^3 more yield than the digester without baffles, (3) third, the development of both digesters from their initial design to an improved version resulted in the observation of the significant difference in their overall biogas production after 16 days. The data provided the findings that the mean of the digester without baffles is substantially lower than the digester with baffles. It contributed heavily as it detected the possible application and its feasibility of offering sustainable gas in rural communities.

While acknowledging the study's limitations, such as a limited budget, time constraints, and limited laboratory testing, potential areas of the research can be improved, such as testing alternative materials to address the limitations of the used equipment and modifying the timeline to maximize design revisions. To further elaborate, the usage of substitute materials for each part of the Anaerobic batch digester can address the used material's limitations to further utilize biogas production. Furthermore, an extension to the timeline in the creation of the product may give room for improvement by maximizing trials to achieve its maximum biogas production.

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