Performance of Biogas Produced by Co-Digesting Dairy Cattle Feces and Cattle Rumen Waste

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***Abstract*—This study aims to identify the performance of biogas made by co-digesting dairy cattle feces and cattle rumen waste. As we know, greenhouse gas emissions from the livestock sector are one of the main factors causing global warming and climate change. This sector accounts for about 14.5% of the total greenhouse gas emissions in the world. One of the contributors to emissions from this sector comes from cattle livestock. The concept of renewable energy can be one of the solutions to reduce the impact of greenhouse gas emissions from the livestock sector. The study used four treatments with different raw material mixtures for biogas. P0 consists of dairy cattle feces only; P1 consists of 75:25 of dairy cattle feces to cattle rumen waste; P2 consists of 50:50 of dairy cattle feces to cattle rumen waste; and P3 consists of 25:75 of dairy cattle feces to cattle rumen waste. Biogas is measured by CH_4 production and flux results. The results showed that the co-digestion of rumen waste with dairy cattle feces increased CH_4 production 2-3 times higher than rumen waste only, and it depended on the ratio of dairy cattle feces to rumen waste. We concluded that rumen waste can be an alternative raw material for biogas production. Optimal biogas production from rumen waste can be achieved if rumen waste is digested together with dairy cow feces (co-digestion) with a composition of 25:75. Optimal conditions refer to both results in CH_4 yield and flux differing significantly from the digestion of rumen waste alone.**

***Keywords*—emissions, biogas, dairy cattle feces, rumen waste, methane, methane flux**

I. Introduction

Greenhouse gas emissions from the livestock sector are one of the main factors causing global warming and climate change. The OECD [1] reported that the livestock sector harms the environment through greenhouse gas emissions, air pollution, and deforestation. Livestock activities produce gases that can cause greenhouse gas emissions from organic waste fermentation of cattle feces, urine, and ruminant waste [2].

The livestock sector is one of the biggest contributors to greenhouse gas emissions. This sector contributes 14.5% of the total greenhouse gas emissions in the world. One of the contributors to emissions from this sector comes from cattle activities. In Indonesia, especially in Central Java, it is stated that greenhouse gas emissions from the livestock sector account for around 76% of total emissions [3]. To overcome this problem, the livestock sector needs to handle good management, including waste management. Pertiwiningrum *et al.* [4] stated in this study that if organic waste from the livestock sector is not treated, methane gas can be released into the atmosphere and cause global warming, while the waste converted to biogas will reduce global warming impact.

The conversion of organic waste to energy by anaerobic digestion through biogas technology is a viable solution to reduce the impact of greenhouse gas emissions. Renewable energy adoption can be implemented by taking into account the waste organic potential and the conditions of the local environment. All organic waste can generate biogas, such as waste from plants and animals. Triatmojo *et al.* [5] stated that biogas production by anaerobic digestion produces not only methane gas (CH_4) but also other gases like carbon dioxide (CO_2) and water vapor. The methane gas can be used as a fuel substitute for fossil fuels. This study aims to identify the biogas performance produced from waste cattle waste, dairy cattle feces, and cattle rumen by an anaerobic co-digestion process. Anaerobic co-digestion refers to the simultaneous anaerobic digestion of multiple organic wastes in one digester. The research is also expected to provide information on the development of biogas from several livestock wastes as an environmentally friendly alternative energy source. Animal byproducts can be used as an alternative substrate in co-digestion. Animal byproducts are defined as parts of animals that are not intended for direct human consumption, like rumen, rumen waste (rumen content), and manure. This study investigated rumen content or waste as a co-substrate in co-digestion. Many studies stated that the co-digestion of rumen waste with lignocellulosic wastes gives outstanding performance in biogas yield. Studies that combine cattle feces and rumen waste are rare. As we know, mono-digestion of cattle manure performs well in biogas yield. The objectives of this study are (1) to contribute to enriching scientific knowledge regarding rumen waste utilization and (2) to investigate the impact of rumen waste when it is added as a co-substrate in co-digestion with dairy cattle feces.

II. Literature Review

The greenhouse gases increase global temperature and have an impact on various aspects. The main mechanism is that greenhouse gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) increase the earth's temperature by absorbing heat from the sun and trapping it in the atmosphere [6].

Nationally, the agricultural sector, including the livestock, plantation, forestry, and fisheries sectors, emits Greenhouse Gas (GHG) emissions of 8%, with the following gas distribution details: CH_4 is 60%, CO_2 is 5%, and N_2O is 15% [7]. GHG emissions from this sector are produced from various activities, including rice cultivation, fertilizer use, land management, animal waste management, and enteric fermentation results from animal digestion [8, 9]. The government committed to GHG emissions by 29%

independently and 41% with international support in 2030 [10].

Biogas is a renewable energy production technology by anaerobic fermentation of organic materials [11]. Anaerobic digestion is a biological process in which organic matter is decomposed by various microbes in the absence of oxygen and produces biogas. The efficiency of anaerobic digestion is highly dependent on the type of raw material [12]. In general, biogas consists of around 55-70% CH_4, 30–45% CO_2, smaller amounts of NH_3 (80 to 100 ppm), H_2S (1000 to 3000 ppm), and hydrocarbons (<100 ppm) [11]. Biogas production depends on many factors, including microbial population, acidity (pH), carbon mass to nitrogen ratio (C/N ratio), operating temperature, substrate particle size, organic loading rate, hydraulic retention time, total solids content, and reactor configuration (batch or continuous, one or two stages), as well as the pressure, temperature, and raw materials used [13, 14].

Anaerobic mono-digestion is the process of decomposing organic matter by anaerobic bacteria in the absence of oxygen with one type of raw material. This process produces biogas with a content of 50–75% CH_4 and 25–50% CO_2 [15]. Double anaerobic digestion (co-digestion) is an anaerobic digestion process that combines two or more types of raw materials. This process can improve the efficiency of anaerobic digestion and produce more and higher-quality biogas [16].

According to Hamzah *et al.* [17], livestock waste that emits high potential GHG emissions is cattle feces. Improper treatment of feces waste can lead to the release of harmful pathogens and air pollution. Livestock manure produces about 55–65% CH_4 and can cause a 21 times increase in global temperature more strongly than CO_2 [18]. Livestock manure is a good raw material for producing methane-rich biogas. Besides feces, rumen is also waste in the livestock sector, which has a potential resource that can be utilized as raw material in biogas. Rumen waste contains a lot of lignocellulosic biomass that has not been fully digested, which can be used as an energy source by microorganisms [19, 20]. The high microbial diversity in the rumen channel enhances the fermentation process, resulting in faster and greater amounts of biogas [21]. Mixing raw materials in biogas processing can be one way to help increase the activity of anaerobic microorganisms by providing nutrients, increasing buffering capacity, and diluting toxic compounds [22].

III. Materials and Methods

A. Material

The materials used in this research include dairy cow feces, cattle rumen from a cattle slaughterhouse, a batch-type digester, a thermometer, a pH meter, a vial closure, aluminum foil, a syringe, a venoject plain, and pot labware. Dairy cattle feces were collected from the Livestock Center of Animal Science Department at Universitas Gadjah Mada, while cattle rumen waste was collected from a slaughterhouse in Sleman City, Yogyakarta, Indonesia.

B. Methods

This research took place in 4 stages: (1) tool preparation, (2) material preparation, (3) biogas production and (4) data analysis.

1) Tool preparation

The preparation of the tool includes the tool designing of co-digesters. The co-digester is assembled from a 20-liter plastic tub container equipped with a thermometer. The container has a diameter of 26.5 cm and a height of 36 cm. The components required on a single co-digester unit are a fan, an alcohol thermometer, a vial cap, a manometer, and a connecting hose. The digester design can be seen in Fig. 1.

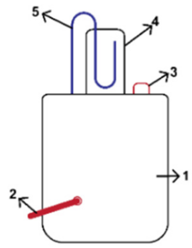

Fig. 1. Digester components.

Information:
1) Digester
2) Thermometer
3) Vial Closure
4) Manometer
5) Hose

2) Material preparation

This study consists of 4 treatments with a mixture of raw materials as shown in Table 1.

Table 1. Comparison of biogas raw material composition

Treatment	Composition of Biogas Substrates
P0	dairy cattle feces
P1	dairy cattle feces: rumen content = 75:25
P2	dairy cattle feces: rumen content = 50:50
P3	dairy cattle feces: rumen content = 25:75
P4	pure dairy cattle feces
P5	pure rumen waste

For every treatment in P0 until P3 samples, 50% mass of water was added before the anaerobic process started. The P4 and P5 samples were raw material substrates.

3) Biogas production

Biogas raw materials were prepared following the formula in Table 1. The ingredients were mixed according to the ratio in each treatment (Table 1) until they became homogeneous and then closed tightly to minimize outside air. The anaerobic co-digester was operated at ambient temperature for 40 days. Gas sampling was carried out periodically every 10 days throughout the digesting process, continuing until 40 days, with gas sampling done three times using a syringe. The gas was then transferred into the venoject. Before each gas sampling, the fan must be turned on to make the gas in the co-digester homogeneous. In addition, this study also analyzed other indicators like temperature, initial and final pH, C-organic (using the Walkley and Black method), N content (Kjedahl method), and C/N ratio of materials. The collected data were analyzed statistically using the One-Way Analysis of Variance (ANOVA) and the Tukey Test.

4) Data analysis

a) Biogas production

Biogas production was indicated from the CH_4 yield of gas samples that were analyzed using the Gas Chromatography test, which is a chemical analysis method used to separate and identify chemical components in a mixture. Gas Chromatography testing was carried out at the Laboratory of the Agricultural Environmental Instrument Standard Testing Center, Pati, Central Java.

b) Methane flux calculation

Methane flux is the flow rate of CH_4 emitted from organic waste into the atmosphere at a certain time. It was obtained from a gas sample that had been analyzed using the Gas Chromatography method and calculated using the following formula.

$$CH_4 \text{ flux} = \frac{dc}{dt} \cdot \frac{Vch}{Ach} \cdot \frac{mW}{mV} \cdot \frac{(273,2)}{(273,2+T)}$$

Information:

CH_4 flux (mg/m^2/min)
DC/DT: difference in CH_4 concentrations (ppm)
Vch : volume of plastic tub container (m^3)
Ach : area of plastic tub container (m^2)
Mw : weight of CH_4 molecule (g)
mV : volume of CH_4 molecule (22.4 L)
T : average temperature of gas sampling

IV. Result and Discussion

A. Biogas Production

1) Characteristics of biogas

The characteristics of the raw materials are very important for the biogas yield. This study considers the mixture of dairy cow feces and rumen contents with different raw material composition ratios and their impact on biogas production. The raw materials analyzed for composition include acidity (pH), temperature, and C/N ratio. The analysis is carried out before the raw materials are put into the digester (initial C/N ratio) and after anaerobic fermentation (finish C/N ratio). Table 2 shows the results of the characteristics of raw materials of biogas in each treatment.

Table 2. Results of analysis of biogas raw material characteristics with comparison of different raw material compositions

Treatment	Characteristics of raw materials			
	pH	Temperature (°C)	Initial C/N ratio	Finish C/N ratio
P1	6.7	27	5.25 ± 0.10^a	3.43 ± 0.73^a
P2	6.8	27	5.06 ± 1.58^a	3.93 ± 0.43^a
P3	6.8	27	7.80 ± 10.48^b	6.58 ± 0.43^b
P4	6.8	27	18.21 ± 65^d	10.46 ± 0.97^c
P5	4.5	27	16.69 ± 0.59^d	7.08 ± 0.55^b

Description: ^{a,b,c,d} superscripts indicate test results of the ANOVA followed the Tukey test. The mean value followed by the same letter (^{a,b,c,d} superscripts) is not significantly different according to the Tukey (HSD) test at the 0.05 significance level; ± refers to std. deviation.

a) Degree of acidity (pH)

The pH of the material before being put into the digester at the raw material of dairy cattle feces (P4) was 6.8, while rumen waste (P5) was 4.5. The pH values in all treatments had results that were not far apart. Erkus and Tuncay [22] reported that the ideal pH to start anaerobic digestion is between 5.5 and 8.5. The pH values in dairy cattle feces were in an acceptable range so that the anaerobic digestion process could work properly. In contrast, the rumen waste had an initial pH of 4.5. It is not ideal for anaerobic digestion. In low pH conditions, the activity of microorganisms is low, potentially leading to failures in the anaerobic digestion process. In this study, the low pH value of the rumen contents was not the reason for implementing the double co-digestion of the rumen waste with dairy cattle feces. The addition of raw materials is expected to support the pH value to the desired level.

b) Temperature

The anaerobic digestion process can take place at temperatures ranging between 50–55°C, and the optimal temperature is at 35°C. The rate of methane gas (CH_4) production will increase as the temperature increases, but at temperatures that are too low or too high, the rate of gas production will drop drastically because the bacteria are inactive at extremely high or too low temperatures and can slow down metabolic processes [4, 5].

Three types of bacteria play a role in anaerobic digestion, namely psychrophilic, mesophilic, and thermophilic bacteria [23]. Psychrophilic bacteria work at a temperature of 10–20°C, mesophilic bacteria work at a temperature of 20–35°C, and thermophilic bacteria work at a temperature of 45–60°C. The results of temperature observation showed that all treatments underwent a digestive process in the mesophilic. The anaerobic digestive process that takes place in mesophilic conditions is generally more stable and more resistant to inhibitory substances, such as ammonia and long-chain fatty acids [24].

c) C/N ratio

In the P4 treatment, which used dairy cattle feces, the C/N ratio was (18.21±0.65), while in the P5 treatment, which involved rumen contents, the ratio was (16.90±0.59). The C/N ratio between treatments P4 and P5 has a value that is not much different. The C/N ratio content in the mixture had the highest level in the control treatment (P0) and the lowest level in the treatment (P2). Hagos *et al.* [25] stated that the anaerobic digestion process runs optimally if the C/N ratio of ingredients is around 20–30. This ratio is sufficient to meet the energy and nutrient needs of microorganisms. Therefore, the C/N ratio is one of the important factors that must be considered in selecting raw materials for the double anaerobic digestion process (co-digestion).

The mixing treatment with different raw material compositions has a C/N ratio of less than 8, except for P0. A C/N ratio below 8 may lead to the suppression of bacterial activity. Such a low C/N ratio indicates an abundance of nitrogen in the material, which can be released in the form of ammonia. This release can raise the pH level in the digester and cause inhibition of bacterial metabolism [4, 5].

2) Methane Production

The decomposition of organic matter by microorganisms in anaerobic digestion will produce CH_4, CO_2, and small amounts of other gases. In the research carried out, which uses raw materials in the form of a mixture of dairy cow manure and rumen contents with a comparison of different raw material compositions, gas sampling is carried out consecutively at the intervals of the 10th, 20th, 30th, and 40th days. Sample testing was carried out by the Gas Chromatography method, and data on CH_4 concentration was obtained in the form of ppm, which is the number of CH_4

molecules in one million gas or liquid molecules. Table 3 presents the testing results of CH_4 content.

Table 3. Methane (CH_4) concentration in the comparative analysis of biogas raw material composition

Replication	CH_4 concentration (10^3 ppm)					
	P0	P1	P2	P3	P4	P5
1	772.72	713.48	622.37	693.86	774.20	270.77
2	739.70	786.35	587.56	709.04	779.33	234.18
3	800.65	823.31	590,53	708.68	780.36	227.99
Average	$771.03{\pm}30.51^{c}$	$774.38{\pm}55.89^{c}$	$600.15{\pm}19.30^{b}$	$703.86{\pm}8.56^{c}$	$777.96{\pm}30.00^{c}$	$244.32{\pm}23.12^{a}$

Description: ^{a,b,c} superscripts indicate test results of the ANOVA followed the Tukey test. The mean value followed by the same letter (^{a,b,c} superscripts) is not significantly different according to the Tukey (HSD) test at the 0.05 significance level; $\pm$ refers to std. deviation..

Based on the results of statistical analysis, the CH_4 concentration in the treatment P0 as a control was $(771.03{\pm}30.51).10^3$ ppm. In the treatment P1, the concentration was $(774.38{\pm}55.89).10^3$ ppm, P2 had a concentration of $(600.15{\pm}19.30).10^3$ ppm, and P3 recorded a concentration of $(703.86{\pm}8.56).10^3$ ppm. The statistical analysis indicated a significance value of ($p<0.05$), suggesting that there was significant difference in the mixing treatment. Tukey's continued test showed that the treatments P1, P2, and P3 were significantly different from P5, and the treatment P2 is significantly different from P0, P4, and P5. This showed that the mixing treatment (rumen waste and feces) with compositions of 75:25, 50:50, and 25:75 demonstrated a significant increase in CH_4 yield when rumen waste is co-digested with feces. Table 2 shows that the P2 treatment with a 50:50 mixture composition resulted in the lowest CH_4 production compared to P1 and P2. The co-digestion that had the highest CH_4 yield was the P1 treatment (feces: rumen = 75:25), achieving a yield of $(774.38{\pm}55.89).10^3$ ppm. However, the value did not show a significant difference when compared to the P0 and P4 treatments. It means that the co-digestion of waste rumen with dairy cattle rumen (75:25) will result in CH_4 yield that is similar to that obtained from mono-digestion of dairy feces only.

The value of the CH_4 concentration produced by each raw material can differ due to various factors. One of the factors that can affect the CH_4 production value is the C/N ratio value. This process produces CH_4 gas, the amount of which can be influenced by the type of feed, especially the fiber and protein content. The higher the content of organic matter and fiber, and the more easily decomposed by microorganisms, the more CH_4 gas can be produced. It can be assumed that the feces used come from cows whose feed has a good source of feed to produce CH_4. In the C/N ratio analysis, the mixture of raw materials has a low C/N ratio value, indicating that the mixture of raw materials lacks carbon content. This result is in line with the nitrogen content obtained in dairy cow feces and cow rumen contents, both of which have a fairly high nitrogen content so that when both materials contain quite high nitrogen, they will produce a low C/N ratio. Biogas can be produced from various sources, but some criteria must be met so that the manufacturing process runs smoothly. Organic materials are a potential source of energy that can be used to produce biogas, which contains carbon as the main component of organic molecules, hydrogen as a component of water, and nitrogen as a component of protein and nucleic acids. The selection of raw materials for producing biogas must follow several characteristics and parameters, such as CH_4 potential, particle size, pH, and C/N ratio. These characteristics are quite important because they can be used to optimize CH_4 methane production. The anaerobic digestion process can produce quality biogas at neutral pH and C/N ratios between 20 and 30. Therefore, it is necessary to mix the types of materials that have a balanced composition and can produce high CH_4. Hagos [25] stated that the materials used for anaerobic digestion must contain nutrients needed by microorganisms, both in the form of energy sources and other important components for the growth of microorganisms. Mixing nitrogen-rich materials such as animal feces and carbon-rich materials such as rice straw can be an ideal mixture of materials to increase emissions of methane (CH_4).

In this study, even though rumen waste (P5) and dairy cattle feces (P4) have almost the same C/N ratio, the rumen pH is very acidic, so co-digestion treatment needs to be carried out to create optimal conditions for producing biogas by co-digestion. The co-digestion of rumen waste with dairy cattle feces makes the optimal condition for biogas production achieved (neutral pH).

B. Methane Flux

Methane emissions refer to the amount of CH_4 released into the atmosphere over a specified period. Methane concentration data (CH_4) indicate the quantity of methane (CH_4) present in a material at a specific point in time and are used to determine the flux of methane (CH_4). Flux data, which represents the rate of change in CH_4 concentration, is then utilized to calculate methane emissions (CH_4). Table 4 represents the results of the CH_4 flux for treatments with different compositions. It is important to note that P4 consists of pure dairy cattle feces without added water, while P5 consists of pure cattle rumen waste.

The results of the CH_4 flux calculation showed that the CH_4 emission value in the P0 treatment as control was $(196.72{\pm}32.02).10^5$ mg/m^2/min. The P1 treatment exhibited an emission value of $(339.48{\pm}11.50).10^5$ mg/m^2/min, while the P2 treatment recorded $(155.61{\pm}11.37).10^5$ mg/m^2/min. Lastly, the P3 treatment demonstrated the highest emission value of $(425.97{\pm}12.73).10^5$ mg/m^2/min. The results of the statistical analysis showed a significance value ($p<0.05$), so there was a real difference (significant) in the raw material mixing treatment. The Tukey test showed that the P0 treatment was significantly different from the P3 treatment, which produced the highest CH_4 emission every minute. Therefore, it can be concluded that the raw material mixing composition of 25:75 captured CH_4 emissions optimally. This result is similar to Zheng *et al.* [26] report, which examined the co-digestion of dairy manure with switchgrass at different ratios. The optimal ratio of substrates will optimize anaerobic digestion. The optimal ratio of 25:75 (dairy cattle feces to rumen) resulted in the highest CH_4 flux due to enhanced bacterial community synergy. P2 treatment with a 50:50 mixing composition produced the lowest emissions of CH_4, which are not significantly different from those observed in P0 and P5. This means that P2 cannot be an ideal treatment for capturing CH_4 gases optimally. Based on the results of P4, it is known that dairy cattle feces produce emissions of (443.59±18.44).10^5 mg/m^2/min and rumen contents of (221.20±6.61).10^5 mg/m^2/min. Dairy cattle feces have the potential to produce greater CH_4 emissions than rumen contents.

Table 4. Methane flux (CH_4) in treatment with a comparison of biogas raw material composition

Replication	Flux CH_4 (10^5 mg/m^2/min)					
	P0	P1	P2	P3	P4	P5
1	206.46	329.30	243.94	411.35	423.57	228.72
2	160.95	337.18	225.72	431.91	431.91	218.87
3	222.75	351.96	216.71	434.64	459.89	216.02
Average	196.72±32.02^{a}	339.48±1.50^{bc}	155.61±11.37^{a}	425.9±12.73^{c}	443.59±18.44^{c}	221.20±6.61^{ab}

Description: ^{a,b,c} superscripts indicate test results of the ANOVA followed the Tukey test. The mean value followed by the same letter (^{a,b,c} superscripts) is not significantly different according to the Tukey (HSD) test at the 0.05 significance level; ± refers to std. deviation.

C. Limitations of Study

While the findings of this study provide valuable insights into biogas production or slaughterhouse waste handling through co-digestion, several limitations should be acknowledged. There are many drawbacks to this study. First, the sample size and experimental conditions were limited to a single geographical location and specific livestock waste or feed. Variability in environmental factors such as temperature, humidity, and differences in livestock diet could influence the co-digestion outcomes in broader applications [24, 25].

Further studies might consider larger sample sizes and more diverse settings to enhance the generalizability of these findings. Furthermore, this study utilized a controlled-bed type digester, which may not be fully replicated in common industrial applications. This limitation suggests that results should be interpreted cautiously when extending conclusions to large-scale co-digestion systems. Future research could explore several promising avenues:

- Optimizing substrate ratios. Research can examine additional ratios of dairy cattle feces to rumen waste to identify combinations that may yield higher or more efficient CH_4 emissions under different operational conditions [26]. This will involve mixtures with other organic materials to optimize an ideal C/N ratio, thereby enhancing CH_4 yield [27].
- Environmental condition variability. Investigating the performance of co-digestion under various environmental conditions, such as mesophilic versus thermophilic temperature and varying pH levels [23]
- Advanced reactor designs. Future studies could assess the effectiveness of digester designs, such as continuous flow or two-stage systems, to better understand their impact on CH_4 yield.

V. Conclusion

Based on this study, rumen waste as biogas raw material will not be ideal if processed by mono-digestion because rumen has an acidic pH. The co-digestion of rumen waste with dairy cattle feces is recommended for biogas production. The effect of co-digestion of dairy cow feces and rumen contents on CH_4 production with compositions of 75:25 (P1) and 25:75 (P3) gave the same methane production results (not much different/significant) compared to mono-digestion of dairy cattle feces. However, it is significantly different compared to mono-digestion of rumen waste (P5). It means that the utilization of rumen waste in biogas as raw material will be optimized when co-digested with dairy cattle feces (P1 and P3). There is an increase in methane yield of 2-3 times from mono-digestion of rumen only (P5).

The anaerobic co-digestion of rumen waste and dairy cattle feces resulted in the highest CH_4 yield and the fastest CH_4 flux when the ratio of dairy cattle feces to rumen content was maintained at 25:75. This study indicates that the optimal biogas production from rumen waste will be achieved if rumen waste is digested together with dairy cow feces with a composition of 25:75. Optimal conditions refer to both results in CH_4 yield and flux differing significantly from the digestion of rumen waste alone.

The co-digestion of rumen waste with dairy cattle feces has more desirable properties in biogas production compared to the mono-digestion of rumen waste. Co-digestion is also an eco-friendly approach to handling slaughterhouses' waste problems and turning them into energy. As a result, slaughterhouses' waste conversion can help reduce GHG emissions.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ambar Pertiwiningrum oversees the technical research, Pamungkas Aji Wicaksono conducts data curation, and Margaretha is responsible for data analysis. All the authors discuss the methodology, with Pamungkas drafting the initial draft, Margaretha handling the review & editing process, and Ambar managing the validation and approval stages.

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