RESEARCH PAPER

Biogas Production from Co-digestion Between Rice Straw and Food Waste with Pilot Scale

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Abstract

This study presents a pilot scale design for biogas production from the co-digestion of rice straw and food waste on a pilot scale, as well as the use of cow dung as microorganisms to determine the efficiency of the 3 m^3 pilot scale reactor. The operational of the pilot scale was referred to as laboratory conditions. In terms of a reactor in the laboratory scale was 10 L completely mixed. pH was operated within 6.0–7.5. The highest percentage of methane and cumulative methane production was 70.17% and 11,387.50 ml, respectively. The H_{max}, R_{max} and λ were obtained 12,597.88 mL, 553.93 mL day^{-1} and 6.53 day ($R^2 = 0.98$), respectively. In terms of the pilot scale 3 m^3 presented a percentage of CH_4 55–56% during fermentation time. Biogas production from the pilot scale was presented at 1.604–2.157 m^3. The H_{max} and R_{max} were obtained at 16.95 m^3 and 0.32 m^3 day^{-1} ($R^2 = 0.99$), respectively. Then, the calculation of GHG reduction was presented GHG baseline and project. The GHG reduction in this research was 18.33 kgCO_2eq. The pilot scale biogas digester is useful food waste, rice straw, and cow dung management tool for global warming reduction. This research provides a small-scale biogas production that is useful for food waste, rice straw, and cow dung management tools for reducing global warming impacts. Finally, this research can be carried out towards to the sustainable development goals (SDGs) 12.4, reducing waste through the reuse and recycle process, and SDGs 7 ensuring everyone can access affordable sustainable energy.

Highlights

1. Biogas production from co-digestion between rice straw and food waste through pilot scale, and use of cow dung as microorganisms.

2. High methane percentage from the lab scale and pilot scale that 70.17 and 56%, respectively.

3. The GHG reduction in this research was 18.33 kgCO2eq. The pilot scale biogas digester is useful food waste, rice straw, and cow dung management tool for global warming reduction.

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Introduction

Rice is one of the main agricultural products and export goods in Thailand. In 2019, the total harvested area was approximately 1.93 million hectares, producing rice straw more than 22 million tons per year. For example, rice 1 kg will get rice straw for 0.7–1.4 kg, that's the volume of rice straw depends on the varieties of cultivated rice, cutting position and topography which is a concern with humidity and temperature. Unfortunately, after harvesting the farmers usually clear up rice straw in their fields by fire (open burning). This is what causes air pollution and degrades soil surface quality. Open burning of rice straw results in the release of air pollutants

such as carbon monoxide (CO), volatile organic compounds (VOC), and particulate matter (PM). The open burning of rice straw can release pollutants into the environment, affecting human health; additionally, asthma in children has increased (Tipayarom and Kim 2007). The air pollution from rice straw residue open burning has occurred in the central, lower northern, and northeastern regions in Thailand which can impact regional climate change and transboundary air pollution (Junpen et al. 2018). Previous research, Junpen et al. (2018) found the emissions from rice residue open burning include: CO_2 5.34 Mt, CH_4 44 kt, CO 422 kt, SO_2 2 kt, PM_{10} 43 kt. Although rice straw open burning is the main problem of air pollution, the rice straw is parts after harvesting paddy that has fiber which is useful. Rice straw is one lignocellulosic material. There are 3 major fibers contained in rice straw cellulose 36.5%, hemicellulose 33.8% and lignin 12.3%, respectively (Nie et al. 2013). Cellulose is a polysaccharide composed of − 1,4 linked d-glucose units (Bai et al. 2019). Hemicellulose structure is heteropolymer composed of pentoses, galactose. However, the component of cellulose, hemicellulose and lignin depend on plant or biomass species (Brunner G. 2014). For this reason, it perhaps uses for materials to biogas production. The biogas production is renewable energy through an anaerobic digestion process that can be matched for Thai communities. As a result, it is possible to clean up and recycle garbage at the same time. Biogas is material digestion with a variety of organic substrates and microorganisms to propel the biological process in anaerobic condition. Food waste is an excellent source of biogas because it is easily digested by microorganisms. The potential of food waste recycling from municipal solid waste that a small rate when compared with other municipal solid waste (Bunditsakulchai and Liu 2021). Food wastes contain high amounts of moisture, nutrients, and food waste are a source of greenhouse gas (GHG) emissions because when food waste transport to an open dumping area it can be degraded to methane (CH_4) that greenhouse gas then it will be released into atmosphere (Mirmohamdsadeghi et al. 2019). Food waste was estimated by EPA (United Stages Environmental Protection Agency) that food waste was generated 63.1 million tons from the commercial, institutional, and residential sector in 2018 (EPA 2021). Food waste was caused by several activities, including supermarket food waste, short-lived food products, customer behavior, and a lack of planning in food preparation (Thailand Environment Institute. 2021). Therefore, one important source of greenhouse gas emission is the waste sector, the total emission from the waste sector was 16,771.89 $GgCO_2$eq in 2016 (Thailand. 2021). Food waste exacerbates the climate change crisis with its significant greenhouse gas (GHG) due to food waste contributes around a quarter of greenhouse gas emissions in global (Searchinger et al. 2018). When food waste was transported and embedded in a landfill, it was occurred anaerobic decomposition then methane gas (CH_4) was generated. Methane gas is a greenhouse gas that is 25 times as potent as carbon dioxide (CO_2). Therefore, food waste management must be occurred to solve the food waste problem that leads to the greenhouse gas crisis. Anaerobic digestion (AD) is one solution that can be food waste treatment and energy production with less GHG emission (Thapa et al. 2022). This is an effective solution to minimizing the impact of food waste on the environment. Furthermore, when biogas was produced through co-digestion of food waste, a high proportion of methane was produced because it was organic material with a high calorific value and nutritive value to microorganisms, resulting in efficient methane production that could be increased by several orders of magnitude (Ziana and Rajesh. 2015). Therefore, food waste or kitchen waste is the one suitable material for biogas production that can be co-digestion with another material. Previously, there are many research on biogas production from food waste. Bicks AT. (2020) investigated biogas production from local food waste, the result was presented local food waste can be biogas production equivalent to 790.3 m^3. Anaerobic digestion is a technology that can be simultaneous waste management and alternative energy production (Ellacuriaga et al. 2021). Thus, biogas production from co-digestion between rice straw, food waste and cow dung can be led to future sustainability through sustainable development goals (SDGs). Anaerobic digestion starts with hydrolysis, that huge molecule transforms into a smaller molecule and becomes the starter substance in the next process. The second, acidogenesis process, it turns sugar, amino acids, glycerol, and fatty acids into volatile fatty acid by acidogenic bacteria. Volatile fatty acids are including acetic acid, butyric acid, propionic acid, valeric acid, and ethanol. Bacteria will convert volatile fatty acids into acetic acid during the third process, acetogenesis. Finally, methanogenesis process, microorganisms can convert acetic acid into methane, moreover, hydrogen and carbon dioxide also methane production. Afterward, methane can use for alternative energy (Reungsang 2019).

Therefore, the objective of this research is biogas potential production on a pilot scale from co-digestion between rice straw (waste part of harvesting paddy), food waste and cow dung with optimum total solid and evaluate the greenhouse gas reduction of biogas production from food waste, respectively. Hence, renewable energy is alternated with fossil energy and it can be reduced the burning problem in paddy fields and rural areas.

Material and Method

Substrate and Inoculums

This research used rice straw and food waste as substrates (Fig. 1). The rice straw was collected from a rice field in Pathumthani province, Thailand. Food waste was collected from the canteen at the university. After the

collection process, rice straw and food waste were cut to a smaller size for the laboratory scale approximately 1–2 cm and pilot plant approximately 10 cm, respectively. The inoculum was cow dung collected from a cow farm in Pathumthani province, Thailand. Cow dung was removed impurity with a test sieve for laboratory scale.

Experiment Condition in Laboratory Scale

The experiment in a laboratory was operated following the optimum condition from previous research (Budiyono et al. 2010). Materials were fed into the 10 L reactor (Fig. 2), with 2.5% TS. Anaerobic condition was operated with 35–37 °C, pH 7.50, $CaCO_3$ 16 g L^{-1}, and mixing with 105 rpm, respectively (Vanatpornratt et al. 2019). The monitoring parameters were percentage methane production, total gas, and pH, respectively.

Then, the kinetic methane production was calculated with the Modified Gompertz Equation (Eq. 1) (Kathleen and Even 2017). The Modified Gompertz Equation was used to fit the relationship between cumulative methane production during bacteria fermentation time (Zhang et al. 2021).

$$H = H_{max} \times exp\{-exp[\frac{R_{max}e}{H_{max}}(\lambda - t) + 1]\} \quad (1)$$

where H is cumulative methane production (ml) during incubation time, t incubation time (days), R_{max} is maximum production rate (ml day^{-1} or m^3 day^{-1}), H_{max} is methane production potential (ml or m^3), λ is lag phase (day), and e is constant 2.7182818. A confidence interval of 0.95 was chosen for the goodness of fit to the data (Ware and Power 2017).

Pilot Scale Design and Operation

The experiments were operated with a pilot plant anaerobic digestion that was built according to an appropriate design. The cylindrical pilot plant was a one-stage anaerobic digester with a volume of 3 m^3 (Fig. 3) that mixed substrate and inoculum. Substrates and inoculums were stirred by a turbine that obtained electricity from photovoltaic. The turbine in the system can control revolutions with 105 rpm that optimum revolutions refer to laboratory scale. The pilot plant was operated in a mesophilic (35–37 °C) condition due to the weather in Thailand. The temperature was monitored by a thermocouple sensor that was connected to the LCD

Fig. 1 Rice straw, Food waste and Cow dung

Fig. 2 Reactor 10 L in laboratory scale
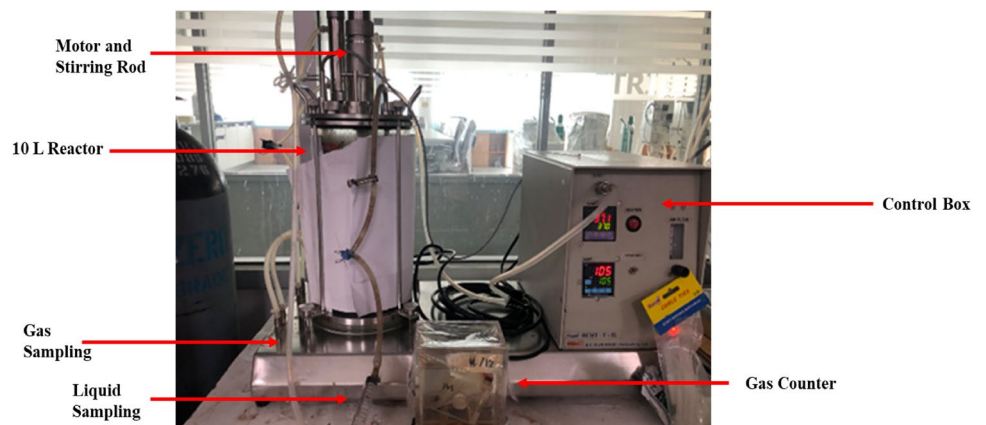
display. The biogas volume (m^3) and percentage of methane production (%CH$_4$) were monitored by biogas.

The experiment on the pilot scale was operated following the optimum condition from the laboratory scale. Substrates and inoculums were fed into the 3 m^3 reactor (Petty Patent: 2,303,000,079) (Fig. 3), with 2.5% TS. Anaerobic condition in the pilot scale was operated with 35–37 °C, pH 7.50, CaCO$_3$ 16 g L^{-1}, respectively. The data were collected every 4 days because of slow digestion. The system was operated and can be started up within 2 months after microorganisms were adapted to anaerobic digestion conditions. Finally, the kinetic methane production was calculated with the Modified Gompertz Equation.

Calculating Greenhouse Gas Emission Reduction from Biogas Production

The greenhouse gas emission was calculated from T-VER TOOL-WASTE method from Thailand Greenhouse Gas Management Organization (Public Organization) that was modified from IPCC (TGO. 2021). The equations were followed as:

$$GHGbaseline(kgCO_2eq) = (Wfood \times EFswdfood) + (Biogas \\ \times Rateofalternativeenergyforfossilfuel \times NCV \times EFfuel) \quad (2)$$

$$GHGproject(kgCO_2eq) = \left(Wfood \times 0.001 \times GWP_{ch4}\right) \\ + (electricityinproject \times EFelec) \quad (3)$$

$$GHGreduction\left(kgCO_2eq\right) = GHGbaseline\left(kgCO_2eq\right) \\ - GHGproject\left(kgCO_2eq\right) \quad (4)$$

where: EF is the emission factor, W$_{food}$ is kg of food waste, EF$_{swd}$ food (kgCO$_2$eq/kg food waste), Biogas (m^3), rate of

alternative energy for fossil fuel (kg/m^3), NCV is a net calorific value (MJ), EF$_{fuel}$ (kgCO$_2$eq/MJ), GWP_{ch4} is global worming potential (kgCO$_2$eq/kgCH$_4$), electricity in the project (kwh), EF$_{elec}$ (kgCO$_2$eq/kwh). The greenhouse gas emission was calculated after the biogas calculation. The boundary of calculating greenhouse gas reduction was started with food waste from the canteen and finished with the utilization of biogas production instead of LPG. In term of the boundary of GHG calculation from this research was present in Fig. 4 that calculate from the dotted line boundary and a methane sensor, respectively.

Result and Discussion

Biogas Production in Laboratory Scale

The optimum condition for biogas production on a laboratory scale was semi-continuous, which was presented within wet anaerobic digestion 2.5%TS, 35–37 °C, pH 7.50, CaCO$_3$ concentrations of 16 g L^{-1}, respectively. Figure 5 shows the change in pH monitoring during biogas production under mesophilic conditions during the fermentation process. The pH profile in this system started at 7.50 because of slow the fermentation process with co-digestion between rice straw and food waste. The biogas production system can be operated at optimum pH due to the alkalinity that is controlled with CaCO$_3$ 16 g L^{-1}. In this study, the pH value that was suitable for anaerobic digestion ranged from 6.0 to 7.5. If the pH of the anaerobic digestion system was lower than 6.0, acid-forming bacteria and methane-forming bacteria would be inhibited, and volatile fatty acids would accumulate (Wainaina et al. 2019).

VFAs (Fig. 6) were found in biogas production steps 2 and 3, where acidogenesis and acetogenesis occurred, and methanogens in the methanogenesis process used acetic

**Fig. 3** Illustrate (3m^3) of the pilot plant used for the biogas production
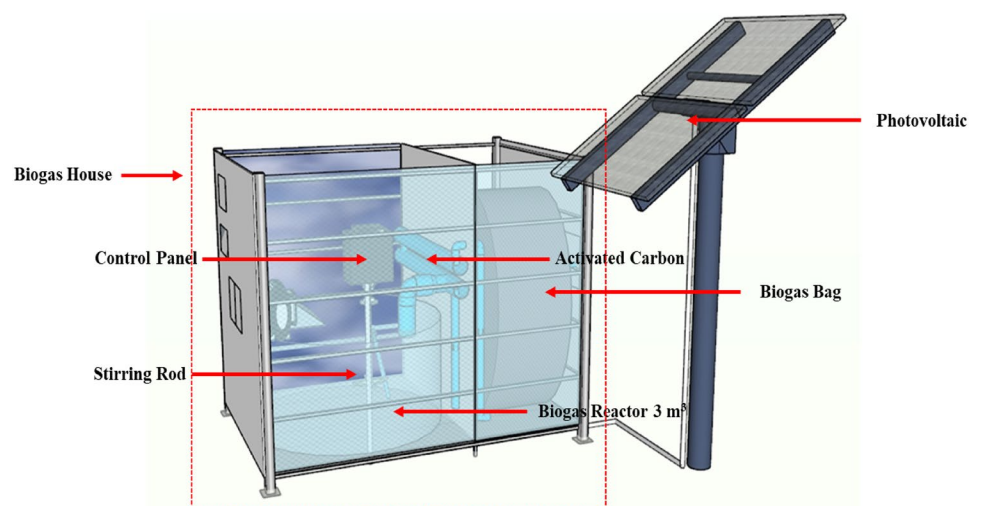
acid to produce methane. However, if VFAs were more accumulated in the biogas production, the system will be failed. When considering the pH and VFAs with percentage methane, cumulative methane production, and kinetic methane production that component of biogas, it was found that biogas production was effective.

In terms of percentage methane production, the reactor was operated for 40 days with TS 2.5% in 0–18 days and 2.5% TS added with 12.5% all working volume reactor after those 19–30 days. The highest percentage of methane was obtained at 70.17% within 28 days (Fig. 7A). The cumulative methane production was obtained at 11,387.50 ml within

Fig. 4 Boundary of GHG calculation using food waste for biogas production
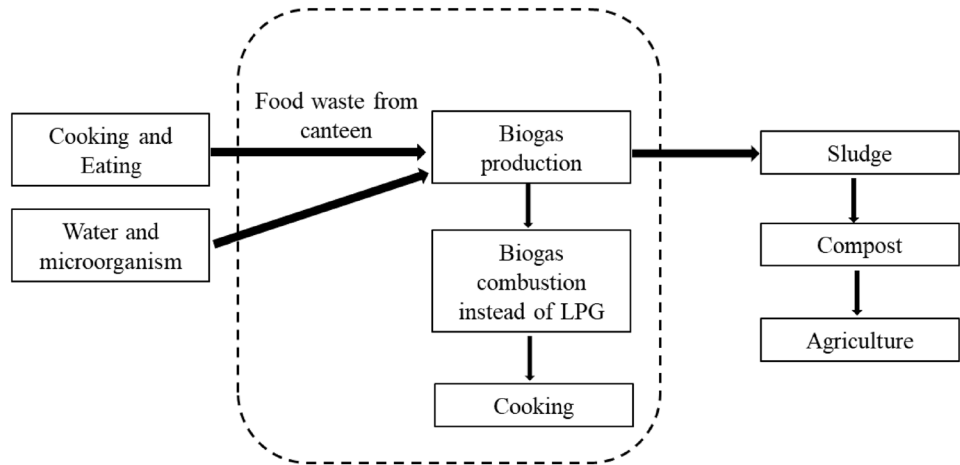
Fig. 5 pH monitoring from biogas production under mesophilic condition during the fermentation period
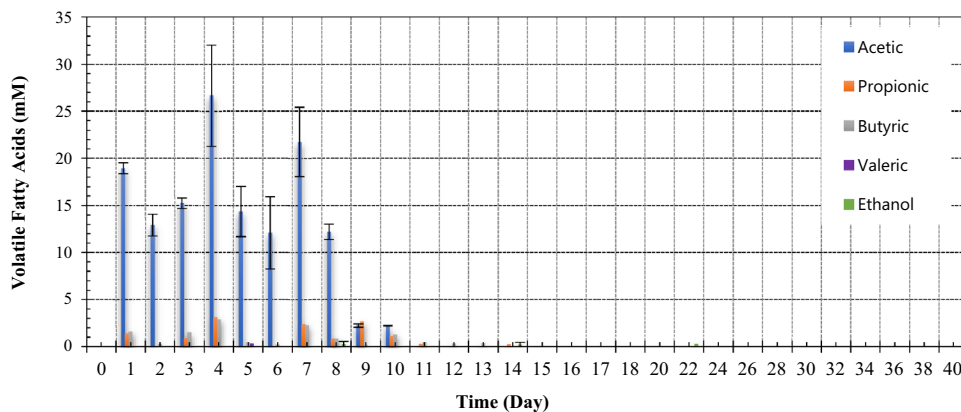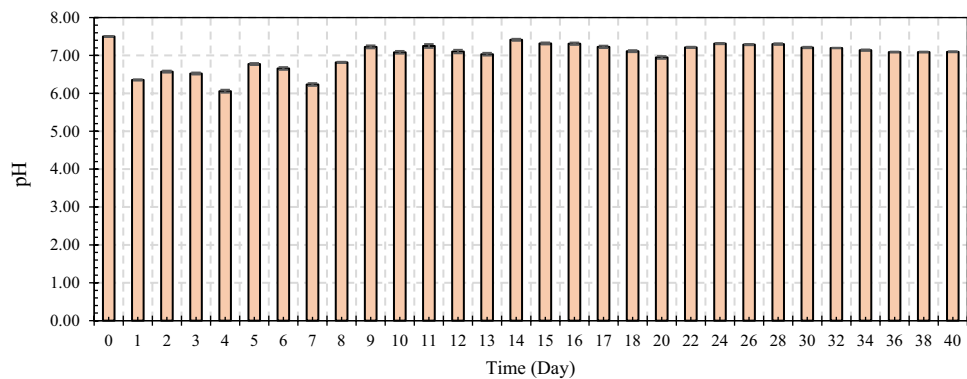
Fig. 6 VFA during biogas production

40 days (Fig. 7B). This research was co-digestion between rice straw and food waste, cow dung as microorganisms. The high methane production in this system can be obtained with co-digestion because food waste is an organic material, high calorific value and nutritive value to microorganisms that led to the efficiency of methane production can be increased by several orders of magnitude (Ziana and Rajesh. 2015). In terms of rice straw is a lignocellulose material that has low digestibility. Rice straw has a high cellulose content and must be pretreated before being fed into a biogas production system (Ngan et al. 2020). However, the pretreatment process can be the alteration of the cellulose structure of lignocellulose rendering fast hydrolysis of both the cellulose and hemicellulose-producing biogas in a short span of time. Therefore, the rice straw used in this research was physically pretreated for alteration of lignocellulose structure to facilitate digestion. The most significant physical pretreatment is a decrease in particle size, which leads to an increase in available surface area and the release of intracellular components (Ghatak and Mahanata 2018).

The kinetic methane production was calculated with the Modified Gompertz Equation. The H_{max}, R_{max} and λ were obtained 12,597.88 mL, 553.93 mL day^{-1}, and 6.53 day ($R^2 = 0.98$), respectively. During the lag phase, the initial breakdown of insoluble materials occurs through the

hydrolysis process. When the substrates broke down, the acidogenesis, acetogenesis, and subsequently methanogenesis phase of exponential gas production occurred (Ware and Power 2017).

Pilot Scale Build and Biogas Production

The 3 m^3 pilot scale (Fig. 8) was built follow illustrate (3m^3) of the pilot plant used for the biogas production in Fig. 3. The startup system after 2 months obtained a percentage methane and biogas production, then the system can be operated within 35 days. Temperature and pH were obtained between 33.0–38.8 °C and pH 6.79–7.21 (Fig. 9). The optimum pH for methanogen was 30–37 °C (temperature of mesophilic bacteria). Mesophilic condition is more robust and less sensitive to changes because of the higher diversity and richness of bacteria in the reactor (Fu et al. 2018). The mesophilic condition was more stable than the thermophilic condition which can be a pH increase, and ammonia will be accumulated in the system, then toxic to the methanogen (Labatut et al. 2014). Therefore, the mesophilic condition was suitable for biogas production.

Although, pH in this anaerobic digestion system was a range of 6.79–7.21, the pH from the anaerobic digestion system was lower than 6.0, acidogenic bacteria are still
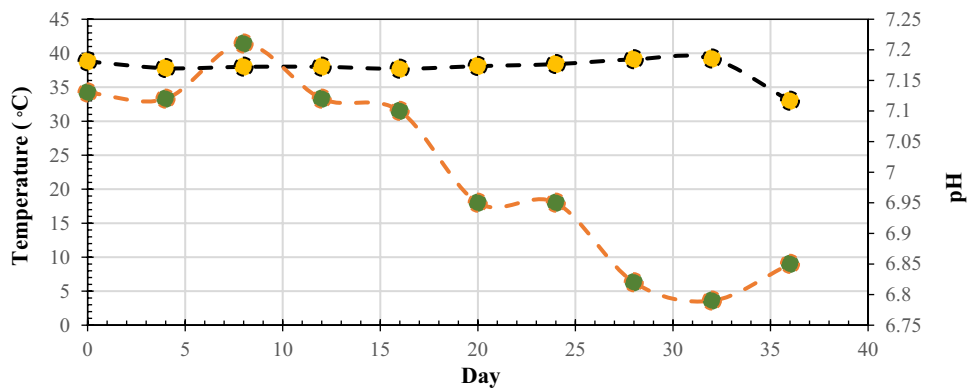
Fig. 7 **A** Percentage methane production, **B** cumulative methane production
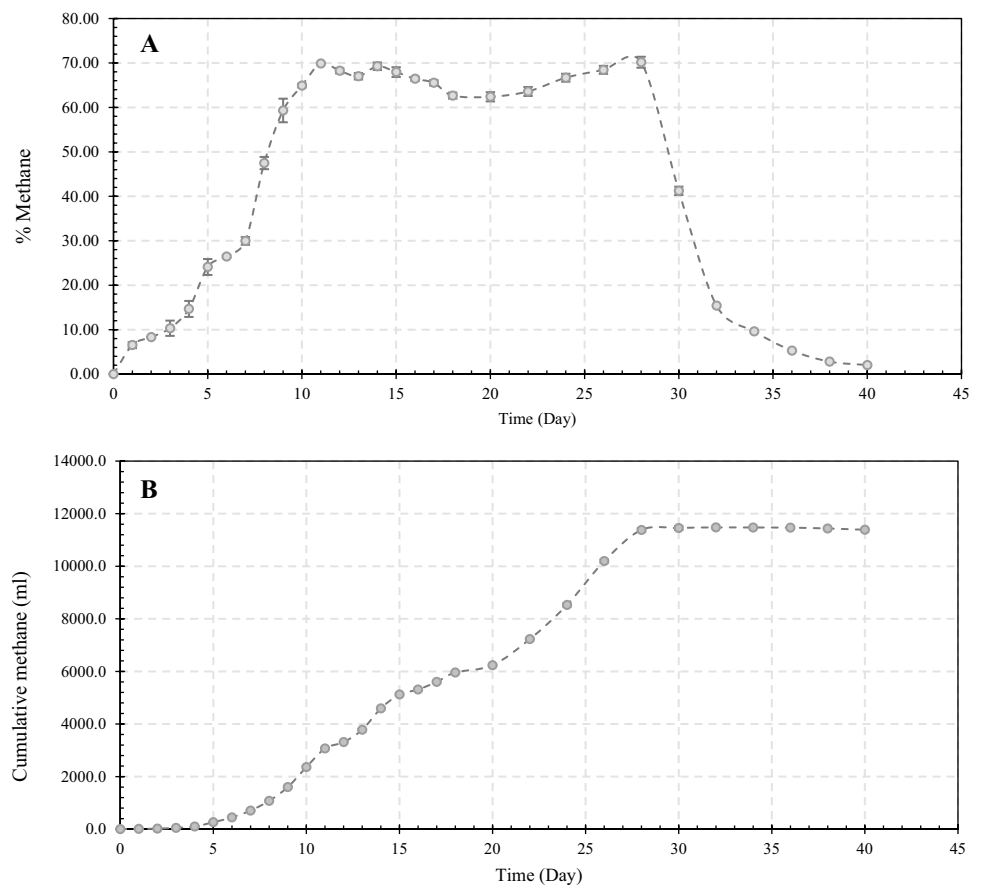
Fig. 8 The 3 m3 pilot scale for biogas production

**Fig. 9** Temperature and pH from 3 m^3 pilot scale reactor

active. However, the methanogenic bacteria was inhibited (Wainaina et al. 2019). During the biogas digestion process, pH usually decreased lower than 6.6 because of the volatile fatty acids in the acidogenesis process (Ngan et al. 2020). The alkalinity in the pilot scale was presented between 1067 and 1383 mg L^{-1} CaCO$_3$.

The alkalinity is an important parameter that led to stable anaerobic digestion. In anaerobic digestion, long-chain fatty acids were formed and accumulated in the system that can be inhibitory at excess concentration and being toxic to bacteria in the system. Moreover, the transportation of nutrients into cells will be inhibited. Therefore, alkalinity monitoring is necessary (Chen et al. 2015).

The percentage of methane production was presented 55–56% (Fig. 10A) during fermentation time. Biogas production from the pilot scale was presented 1.604–2.157 m^3 (Fig. 10B). Methane production was presented at 0.882 m^3–1.208 m^3 (Fig. 10C). The steady
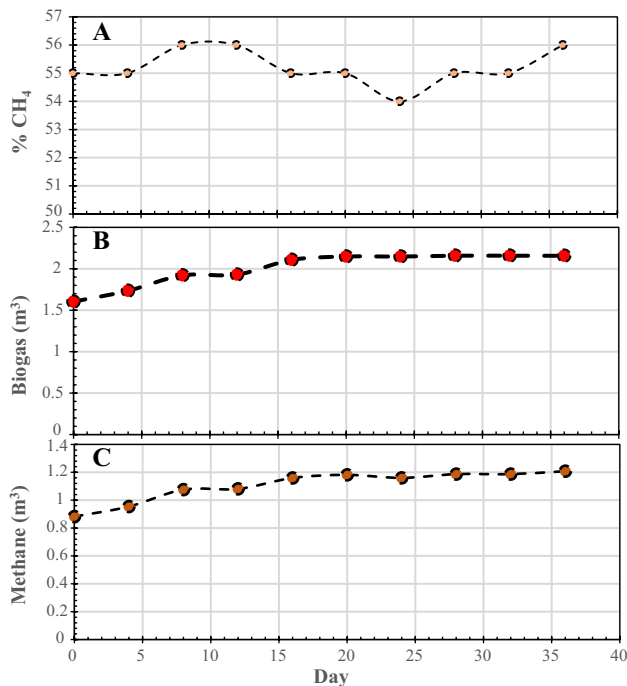
Fig. 10 A Percentage methane production, **B** biogas production and **C** methane production (m^3) in 3 m^3 pilot scale

stage was obtained in 28 days. The biogas production was related to pH in the pilot scale because of the slightly pH decreasing in 28 days. The high biogas production can be obtained with co-digestion between rice straw and food waste because food waste is an organic material, high calorific value and nutritive value to microorganisms that led to efficiency methane production can be increased several order of magnitude (Ziana and Rajesh. 2015). Although, high biogas production can be obtained in a pilot scale system, the start up for the biogas production system was presented in 2 months.

The kinetic methane production was calculated with the Modified Gompertz Equation. The Modified Gompertz Equation was used to fit the relationship between cumulative methane production during fermentation time (Zhang et al. 2021). The H_{max} and R_{max} were obtained at 16.95 m^3 and 0.32 m^3 day^{-1} ($R^2 = 0.99$), respectively.

Table 1 GHG reduction with biogas production from food waste for cooking

GHG baseline	GHG project	GHG reduction
19.08 kgCO$_2$eq	0.76 kgCO$_2$eq	18.33 kgCO$_2$eq

Greenhouse Gas (GHG) Reduction

Biogas production is a flexible form of alternative energy. It can be used for electricity generation, liquefied petroleum gas (LPG), or upgraded for transport fuel (World Biogas Association 2018). According to the biogas production data in this research that can be used for LPG for cooking in the canteen. The pilot scale (3 m^3) was input food waste of 27 kg for biogas production instead of LPG. The calculation of GHG reduction was presented GHG baseline and project (Table 1). The GHG reduction in this research was 18.33 kgCO$_2$eq. The pilot scale biogas digester is a useful food waste management tool for global warming reduction.

Food waste, instead of the landfill, it can be towards anaerobic digestion plants that can be converted to biogas production and compost as a by-product. Therefore, biogas and methane production have the potential for greenhouse gas reduction that can contribute to climate neutrality in 2050.

Conclusion

The research provides a pilot-scale biogas production that utilizes food waste and rice straw as a management tool for reducing global warming impacts. Therefore, the greenhouse gas release from food waste and rice straw will be reduced through this management tool. The highest percentage methane and cumulative methane production at the laboratory scale were 70.17% and 11,387.50 ml, respectively. In terms of the pilot scale, the percentage of CH$_4$ during fermentation time was 55–56%. Biogas production at the pilot scale was presented 1.604 m^3–2.157 m^3. The GHG reduction baseline and project were then presented. The GHG reduction in this research was 18.33 kgCO$_2$eq. Finally, this research can contribute to SDGs 12.4, which aims to reduce waste through reuse and recycling processes, and SDG 7, which aims to ensure that everyone has access to affordable sustainable energy. Therefore, this research can lead to carbon neutrality with food waste and rice straw utilization and convert to alternative energy that reduces greenhouse gas emissions, respectively.

Declarations

Conflict of Interest The authors declare no competing interests.

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