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Electricity and biogas production in portable biodigester-microbial fuel cells: Optimum substrate composition and ratio from organic waste

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ABSTRACT

Organic waste comes from various sources, such as food or vegetable waste and animal manurequickly decomposes in nature, but it significantly impacts the environment and human health, with methane (CH_4) and carbon dioxide (CO_2) from organic waste contributing to global warming, and further harming the environment. This study aims to determine the optimal substrate composition of organic waste from vegetable and cow manure for generating electricity using an integrated anaerobic digestion (AD) and microbial fuel cells (MFCs) system. The experiment used portable biodigester-MFCs systems for households and was conducted for eight weeks. Four biodigester reactors using different ratios of vegetable waste to cow manure were applied: R1 (100%:0%), R2 (75%:25%), R3 (50%:50%), and R4 (0%:100%). The result shows the highest electrical voltage in the third reactor (R3), registering at 0.62 mV, consisting of 50% cow manure and 50% vegetable waste. The highest biogas yield (13,192 ml) comes from the second reactor (R2), with a composition of 25% cow manure and 75% vegetable waste. The addition of cow manure to vegetable waste enhanced electricity production through CH_4 production in an anaerobic digestion process. Based on the above result, substrate composition and ratios are needed to influence the optimum pH and temperature to optimise the metabolic activity of bacteria in portable MFCs efficiently. Among the four biodigester tested, R2, with a 75% vegetable waste to 25% cow manure ratio, achieved the highest biogas yield of 13.192 ml and highest CH_4 content. Conversely, R4, comprising 100% cow manure, produced the smallest biogas volume but achieved the highest CH_4. These findings highlight the significant role of cow manure in biogas production and the challenges of utilising vegetable and organic waste effectively.

Keywords: microbial fuel cells, electricity production, biogas, biodigester, organic waste.

INTRODUCTION

According to the World Bank, approximately 2.01 billion tons of waste are generated annually, with 33% of this waste being left unmanaged (Kaza et al., 2018). In Indonesia, the average waste management rate was 76.81% in urban areas in 2022 and 4.65% in rural areas (BPS, 2020, 2023a). Out of 65 million tons of daily waste generated in Indonesia, 15 million tons were inadequately managed (BPS, 2019). Food waste is organic waste that quickly decomposes in nature but significantly impacts the environment and human health. Moreover, methane (CH_4) and carbon dioxide (CO_2) emitted from organic waste contribute to global warming, further harming the environment through processes such as soil acidification, eutrophication, and stratospheric ozone depletion (Saggar et al., 2004). Meanwhile, odours created from organic waste have health implications (Fang et al., 2022; Schiffman & Williams, 2005) and effect aesthetics (Abdel-Shafy & Mansour, 2018; Mu et al., 2017). Therefore, it is necessary to manage organic waste effectively to mitigate its negative impact.

Organic waste originates from various sources such as food, agriculture, garden, timber, and animal manure. In Indonesia, food waste represents the highest proportion, accounting for 28.57% of total waste (SIPSN-KLHK, 2023). This percentage to 39.33% by 2023 (SIPSN-KLHK, 2023) indicates that domestic waste is the most significant contributor, accounting for 44.44% of waste in 2022 and 44.56% in 2023. Fruit, under mesophilic conditions, can serve as a feedstock for biogas production (Viswanath et al., 1992). Additionally, vegetable waste, predominantly from kitchen or organic waste sources, holds significant potential.

Animal manure poses significant challenges due to its emission of greenhouse gasses (GHGs) such as CH_3, CH_4, CO_2, and N_2O (Leytem et al., 2011, 2017; Owen & Silver, 2015). Even during composting, animal manure emits GHGs, notably CO_2 (Mulbry & Ahn, 2014). However, animal manure also presents opportunities. Ruminant manure, for instance, is a potential substrate for anaerobic digestion (AD) in biogas production. It is rich in nutrients, is a valuable biofertiliser, and contains significant amounts of pathogenic microorganisms (Andriamanohiarisoamanana et al., 2018). Various types of animal manure, including cow, chicken, horse manure, and pig, are utilised as sources for biogas production (Hadin & Eriksson, 2016; Wang et al., 2012).

Producing biogas in AD systems using animal manures can be enhanced by incorporating additive microorganisms. Improving the fermentation process has been shown to increase biogas production (Jafar & Awad, 2021). Evidence suggests that co-digestion, achieved by adding ruminant waste such as cow manure to kitchen waste (Taylor et al., 2009), cow manure to oat straw (Zhao et al., 2018), or cow manure and chicken manure to wheat straw (Wang et al., 2012), resulting in higher CH_4 yields. Previous studies have focused on animal manure from various sources, including cows, horses, goats, rabbits, and chickens (Balagurusamy & Chandel, 2020; Guo et al., 2022; Hadin & Eriksson, 2016; R et al., 2016). Nutrition from ruminant waste and its organic content generates energy from AD (Hadin & Eriksson, 2016).

In addition to producing biogas, organic waste can generate electricity through Microbial fuel cells (MFCs) systems. The bio electrochemical array in MFCs can convert chemical energy from organic waste into electricity through microorganisms acting as catalysts. The electrochemical microorganisms play a significant role in transferring electrons during substrate oxidation in MFCs (Zhang, 2012). Electrons and protons are generated through microbial-catalysed oxidation at the anode, with electrons flowing to the cathode through the external circuit and protons moving through the membrane to maintain electrical balance (Khan et al., 2017). Various materials, such as natural organic matter and complex organic waste, can be utilised for electricity generation through MFCs, which can be combined with wastewater treatment (Oliveira et al., 2013). Theoretically, a wide range of microbes can serve as the catalyst in MFCs (Du et al., 2007). In this study, additional microorganisms are used in the fermentation process of vegetable waste to produce biogas and electricity. This is an approach that has yet to be widely applied in previous research. Thus, the main objective of this study is to observe the optimal variation in substrate composition of vegetable waste and cow manure for generating electricity and biogas using an integration system of anaerobic digester within portable MFCs.

MATERIAL AND METHOD

Materials description

The substrate of biogas in this study are vegetable waste and cow manure (Figure 1). Meanwhile, the design of portable biodigester MFCs is illustrated in Figure 2. The reactor tube is made from polyethylene plastic with a volume of 120 litres. The biodigester's height, body diameter, and weight are 930 mm, 580 mm, and 8.6 kg, respectively. Two pipes are positioned in the reactor, one for the inlet to insert the substrate and the other as an overflow pipe to control the volume of biogas. Inside the reactor, two carbon vanes serve as anode and cathode. Carbon electrode performance is better than platinum in the operating pH range in MFCs (Scott & Yu, 2015). Meanwhile, a multimeter was located at the top of the biodigester to measure the electricity generated by biogas production. A small hole is created at the top of the biodigester to serve as the biogas outlet connected to the biogas bag through a small hose. This bag has a capacity of 0.425 m^3.

Experimental setup

Substrate for biogas is made from vegetables combined with cow manure. The vegetables are collected from the traditional market. This study used four reactors (R1, R2, R3, and R4)

Figure 1. The substrates for biogas: (a) vegetable waste, (b) cow manure

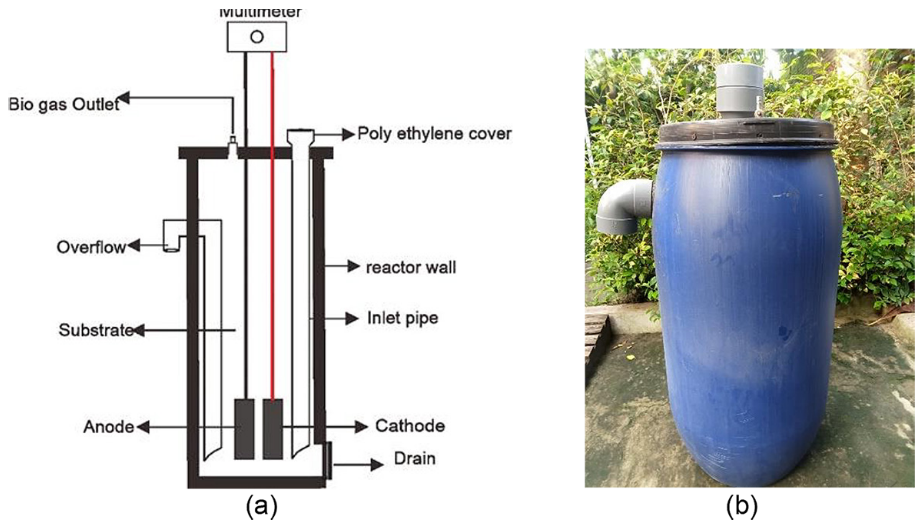

Figure 2. The design of biodigester MFCs: (a) the design of portable biodigester MFCs, (b) portable biodigester in real-world application

to observe the variation in substrate composition between vegetable waste and cow manure in generating electricity and biogas (Table 1). Each reactor is filled with a different composition of vegetable waste and cow manure, with the total volume of each reactor reaching 2/3 of the full capacity of the reactor. Overall, the total amount of substrate used in this study was 44 kg, with an even distribution between vegetable waste and cow manure of 44 kilograms or 100%, respectively. Each reactor is filled with a different mixture to determine optimal electricity and biogas production conditions.

The procedures of the experiment are illustrated in Figure 3. The first step for the experiment is initially setting up to reduce the oxygen inside the biodigester reactor by filling the bioreactor with water until it overflows. This procedure is conducted for a week. After a week, empty the water from the reactor, and all biogas materials are ready to be filled. All substrates, vegetable, and cow manure are filled in

Table 1. Substrate composition between vegetable waste and cow manure in generating electricity and biogas using portable biodigester-microbial fuel cells

Reactor 1 (R1)	The composition is 17.6 kg of vegetable waste, representing 100% of the total substrate and no cow manure (0%).
Reactor 2 (R2)	The composition is a mixture of 13.2 kg of vegetable waste (75%) and 4.4 kilograms of cow manure (25%).
Reactor 3 (R3)	The composition is balanced between 8.8 kg of vegetable waste (50%) and 8.8 kilograms of cow manure (50%).
Reactor 4 (R4)	The composition is 17.6 kg of cow manure, representing 100% of the total substrate without any vegetable waste (0%).

Figure 3. Step for the experiment: (a) biodigester setup, (b) electricity setup, (c) weighing the substrates, (d) loading the vegetable substrate into the biodigester, (e) loading the cow manure into the biodigester, (f) mixing the substrates in the biodigester, (g) taking substrates samples (marked with a red circle) from the biodigester, (h) electricity measurement, (i) collecting gas samples for laboratory testing

each reactor based on the composition in Table 1. All vegetables are cut into small pieces (approximately 0.5 – 0.75 cm) using a knife as the pretreatment. Pretreatment influences process efficiency (Amigun et al., 2008) to optimise biogas production (Shah et al., 2022). The smaller the substrate, the higher the biogas production (Hilkiah Igoni et al., 2008). Researchers do not chop vegetable waste into substrates because this process requires special tools and is expensive and explicatively inefficient. Add water to the reactor until it reaches 75% of its volume. Stir the mixture of substrate and water inside the reactor to prevent scaling. Subsequently, the two carbon vanes are set up inside the reactor, along with a multimeter located outside the reactor to measure the electricity, such as electric voltage (V), electric resistance (Ω), and electrical current (A). The experiment observation was conducted weekly, from week one to eight. The experiment was conducted from December 9, 2022, to January 24, 2023. In Indonesia, this period coincided with the rainy season, and the ambient temperature and humidity in the study location ranged between 24–40 °C and 70–94 humidity in December 2022 (BPS, 2023b). It was assumed that the temperature and humidity in January 2023 were almost similar to those in December 2022. There is an argument that temperature influences biogas production, where the AD can be optimised within the temperature range of 20–68 °C (Ramatsa et al., 2014).

Measurement and analysis

The parameters to assess electricity are electric voltage, electric resistance, and electrical current. These variables are measured by using a multimeter. The energy was calculated using the calculation of power (P), which is a product of current (I) and voltage (V) that is presented in the equation of $P = I \cdot V$. Meanwhile, the gas compounds measured in this study are CH_4, CO_2, and N_2O. These gases are measured using Gas Chromatography 2014 (GC-2014) (Wassmann et al., 2000).

RESULT AND DISCUSSION

Electricity production

MFCs utilise the electrochemical-catalytic activity of microbes to oxidise organic substrates in wastewater, generating electrons for electricity production while simultaneously treating waste (Bajracharya, 2020). MFC performance can be significantly affected by factors such as the type of microorganism used, substrate degradation rate, electrode material, and operational conditions (Prasad, 2023). The electricity parameters generated by MFCs are depicted in Figure 4.

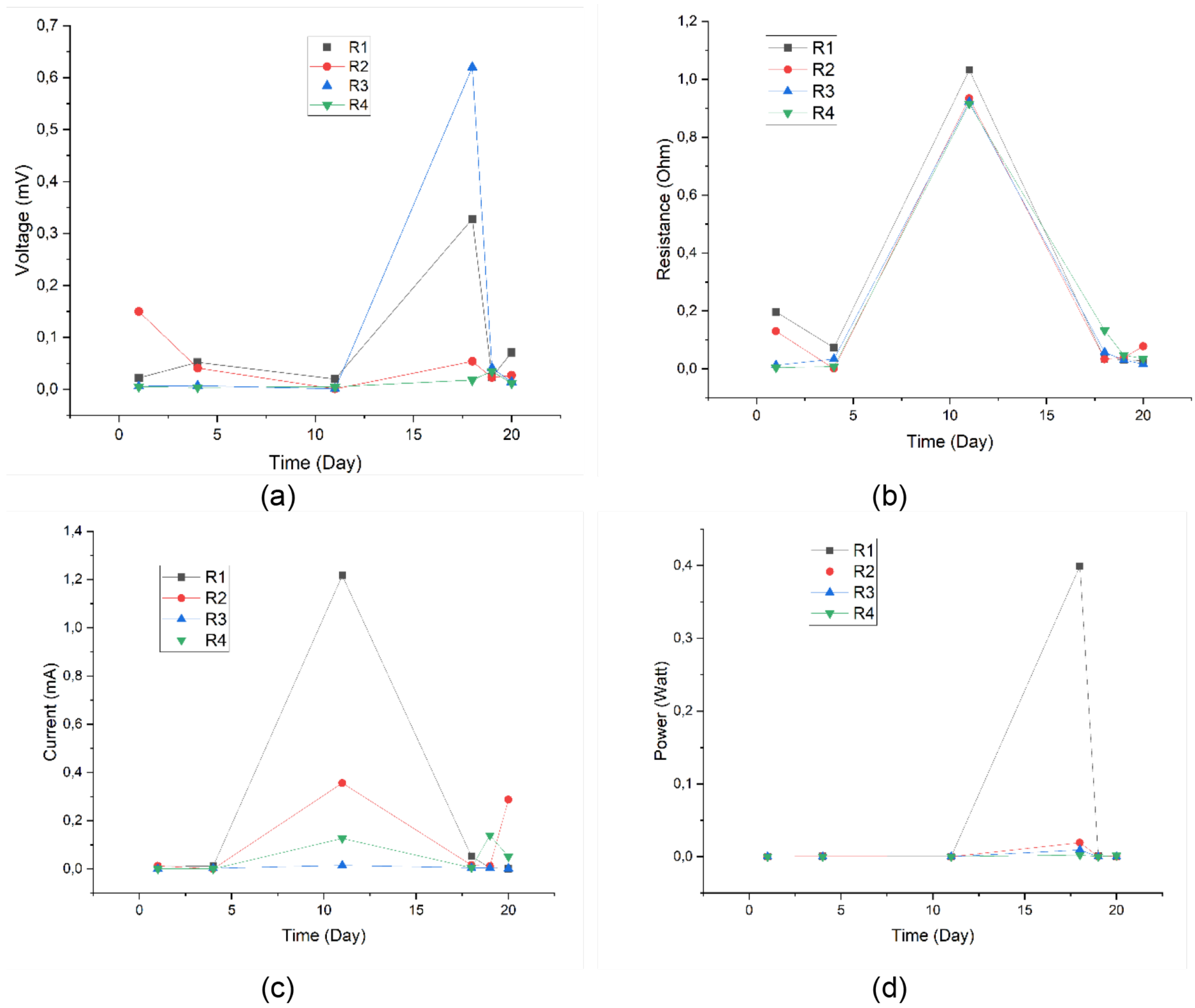

Figure 4. The electricity generation by the MFCs biodigester is presented through: (a) voltage, (b) resistance, (c) voltage over time, (d) the power of electricity

The voltage production across all reactors exhibits a nearly identical trend. It commenced at 0.022 mV, 0.150 mV, 0.006 mV, and 0.005 mV for R1, R2, R3, and R4, respectively. Notably, R3 achieved the highest voltage on the 18th day, registering at 0.62 mV, with a substrate composition of 50% cow manure and 50% vegetable waste. The second-highest voltage, 0.328 mV, was observed in R1 on the 18th day, utilising a 100% vegetable waste substrate. However, on the 19th day, a substantial decline in voltage was recorded for both R3 and R1, dropping to 0.041 mV and 0.024 mV, respectively. In contrast, R2 and R4 did not demonstrate a significant increase in voltage over the same period.

The resistance trends across all reactors exhibits a striking similarity. Regarding current production by the MFCs biodigester, R1 stands out with the highest production, reaching 1.217 mA on the 18th day. The power production in watts (W) is measured. It is observed from Figure 4 that the highest power is achieved on day 18, reaching 0.399 watts. However, the power reduces significantly to 0.001248 W and 0.000355 W on days 19 and 20, respectively. The significant reduction may be caused by the electrode being covered by sludge from the substrate. This should be cleaned to enhance the performance of the electrode.

MFCs create electricity from the metabolic activity of microorganisms, such as electrogenic bacteria. During metabolism, electrons from the bacteria flow to the electrode, generating an electrical current. The electrical current influences the production of voltage. The relationship between electrical current and voltage under various substrate compositions is depicted in Figure 5. Regression models for each reactor are created to identify the relationship, as shown in Table 2. Figure 5 shows that the electrical current in R1 and R3 has a higher slope. This indicates that the current in R1 and R3 contributes significantly to voltage production. The

Table 2. Summary of the regression analysis between current and voltage

Reactor	*p*-value ANOVA	Coeff		R^2 (%)
		Constant	Current	
R1	0.003	0.037 (0.076)	0.238 (0.000) *	96.63
R2	0.173	0.022 (0.078)	0.093 (0,173	51.41
R3	0.006	-0.133 (0.075)	48.21 (0.006) *	94.53
R4	0.960	0.015 (0.006) *	0.009 (0.101)	0.10

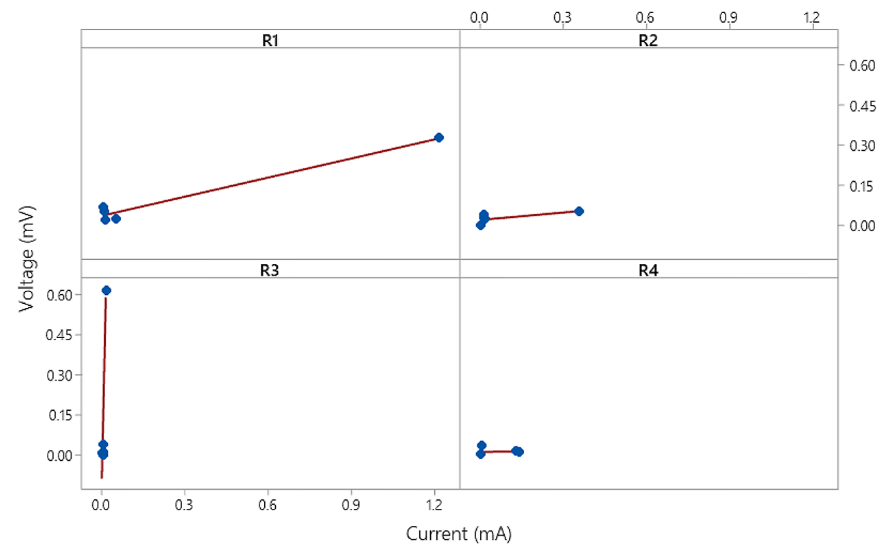

Figure 5. The current and voltage production by the MFCs biodigester in various reactors ANOVA

regression analysis proves that the influence of current on voltage in R1 and R3 is statistically significant but not for R2 and R4.

Differences in substrate composition, electrode performance, and microorganism composition in each reactor likely contribute to the significance of current and voltage. Substrate composition directly influences the metabolic activity of microorganisms in MFC cells. Vegetable waste contains organic compounds such as carbohydrates, proteins, and fats, which microorganisms can break down into energy. Cow manure contains many anaerobic microorganisms essential in decomposing organic compounds into electrons in MFC. Different substrate compositions cause differences in the availability of nutrients and energy sources for bacteria in each reactor. R3 achieved the highest voltage production on day 18 with a substrate composition of 50% cow manure and 50% vegetable waste. This indicates that the microorganisms in R3 efficiently utilise substrate combinations to produce electricity. The substrate composition in R3 encourages the growth of bacteria that are more effective in transferring electrons to the electrode surface, thereby increasing overall current production.

Implementing a two-stage anaerobic digestion method specifically targeting lactate-type fermentation during hydrolysis-acidogenesis increased bioenergy production from food waste (García-Depraect et al., 2022). This stage involves acid production from the hydrolysis of complex organic molecules. Acetic acid bacteria convert hydrolysed organic materials into organic acids, such as acetic acid, propionic acid, and butyric acid. This process produces electrons that can be transferred to electrodes in microbial fuel cells (MFCs), generating electric current and voltage. Microbial fuel cells utilise bacteria, such as those in the rumen, to oxidise cellulose and produce electricity by transmitting electrons to the anode (Rismani-Yazdi et al., 2007). A decrease in voltage was observed on day 19, possibly due to a layer of biofilm adhering to the electrode. Biofilm can inhibit the transfer of electrons from the substrate to the electrode surface (Purwono et al., 2015). The limitation of MCFs in this study is the low production of electricity, which cannot operate at extremely low temperatures because the microbial activity slows down. However, electricity production can be improved by increasing the surface area of electrodes (Rahimnejad et al., 2015). MFC performance is influenced by various operational factors, including the type of bacterial inoculum, fuel substrate and concentration, pH, conductivity, temperature, and operational conditions like hydraulic loading rate (Scott et al., 2012).

Table 3 presents the ANOVA for identifying the relationship among voltage, resistance, and current. They are not influenced by either substrate composition or time because the *p-values* exceed α = 5%, except for resistance and time, which have *p-values* of 0.000. Therefore, another experiment is needed to explore ways to improve the electricity production of biogas.

Biogas volume

The biogas produced through AD consists of CH_4, CO_2, hydrogen sulfide (H_2S), Nitrogen, and water (H_2O) (Andriani et al., 2020). The measurement of biogas volume in this study is conducted in the fifth week. R2 produces the highest volume of biogas, while R4 produces the lowest volume (6452 ml). The biogas volume of R2 is 38.37% higher than that of R1 (9534 ml), 21.33% higher than that of R3 (10,873 ml), and 104.46% higher than that of R4. This result is supported by a previous study, which found that adding cow manure to food waste resulted in the highest biogas production (Taylor et al., 2009; Zhao et al., 2018).

R2 and R3 generated the highest and second-highest gas volumes in this study. However, the

Table 3. Summary of ANOVA test between time, substrate composition and electricity parameters.

Parameter	Factor	*p*-value	R^2 (%)
Voltage	Substrate composition	0.512	48.94
	Time	0.087	
Resistance	Substrate composition	0.323	98.63
	Time	0.000*	
Current	Substrate composition	0.456	46.13
	Time	0.134	

highest CH_4 was produced by R4. Adding cow manure to vegetable waste increases the production of CH_4. This study shows that cow manure produced the highest quality of biogas, with the highest CH_4 and lowest CO_2 and N_2O compared to other substrate compositions. This finding differs from (Taylor et al., 2009), who found that adding kitchen waste increased CH_4. However, the reduction of CO_2 was not significant. The optimal biogas production is achieved when 1/3 cattle manure is added to oat straw (Zhao et al., 2018). Food wastes rich in rapidly degradable carbohydrates and lipids have the potential to generate elevated levels of methane (Kumar et al., 2019).

Biogas production starts from the digestion of organic substrate in vegetable waste. Microorganisms decompose the organic substrate in vegetable waste through biochemical processes. It is fermented to generate CH_4, CO_2, H_2S, and N_2. A previous study produced 0.222 L – 0.258 using a 4 L co-digester from chicken and cow manure (Dankawu et al., 2022). A biogas digester containing high-density polyethylene (HDPE) plastic generates biogas of 4.00 m^3, CH_4 of 2.18 m^3 (54.50%) and CO_2 of 1.77 m^3 (44.25%) using cow manure as the substrate (Obileke et al., 2021).

Vegetable waste plays a significant role in producing biogas because it contains organic compounds that are readily decomposed by microorganisms (Frankowski & Czekała, 2023). Carbohydrates and nutrients in vegetable waste increase microorganism activities as well as CH_4 generation during the fermentation process. Vegetable waste helps balance the fermentation mixture's carbon-to-nitrogen (C/N) ratio. A C/N ratio of 45 increases biodegradability (98%) during co-digestion food waste, cabbage, and cauliflower (Beniche et al., 2021). Cow manure is a source of microorganisms for the anaerobic fermentation process, including in hydrolytic, acidogenic, and methanogenic phases. Gas production in AD is related to a neutral pH and the shift in *archaea*, partially from cow manure, and a prosperous community transition from *Methanosaeta* to *Methanosarcina* (Mukhuba et al., 2020). The methanogenesis stage is essential in the anaerobic fermentation process, as it produces methane. However, electric current production tends to be lower in this stage than in the acidogenic stage because most energy has been converted into methane.

CH_4 and CO_2 production in biodigester-MFCs

The gas composition analysed in the research is CH_4, CO_2, and N_2O. CH_4, CO_2, and N_2O produced by MFCs biodigester are illustrated in Figure 6. CH_4 and CO_2 are renewable natural gases produced from the breakdown of organic materials through AD, which can be found in animal waste, plant residues, and wastewater sludge (Vasantha & Jyothi, 2020). A methane content of at least 40% is essential to ensure that biogas burns efficiently (Eseohe et al., 2022). It is observed from Figure 7a that CH_4 increases over time. R4 and R3 produced higher CH_4 than R2, whilst R1 produced the lowest CH_4. The highest CH_4 level for R1 was 119.88 ppm in week 8. For R2, it was 33,457.86 ppm in week 5. For R3, it was 55,719.09 ppm in week 5, and R4 produced the highest CH_4 in week 8 with 108,821.42 ppm. R4 used cow manure as the only source of organic material (17.6 kg). R4 produced the highest CH_4 compared to R1, R2, and R3. The highest percentage of CH_4 was produced from R4

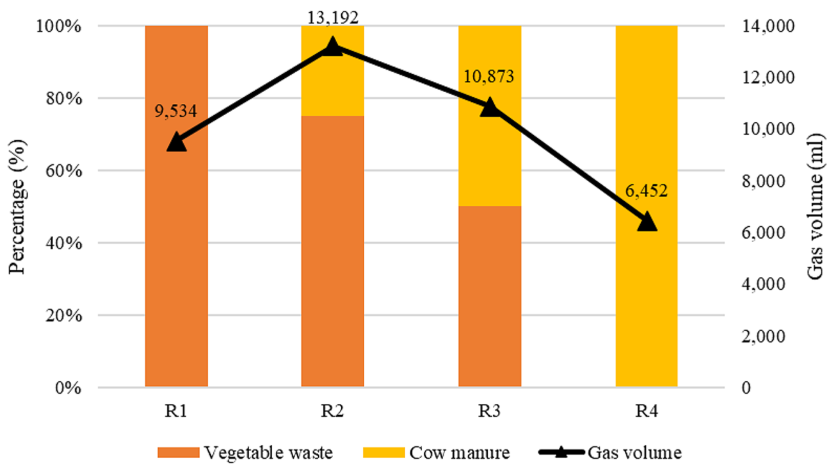

Figure 6. The volume of gas produced by each reactor

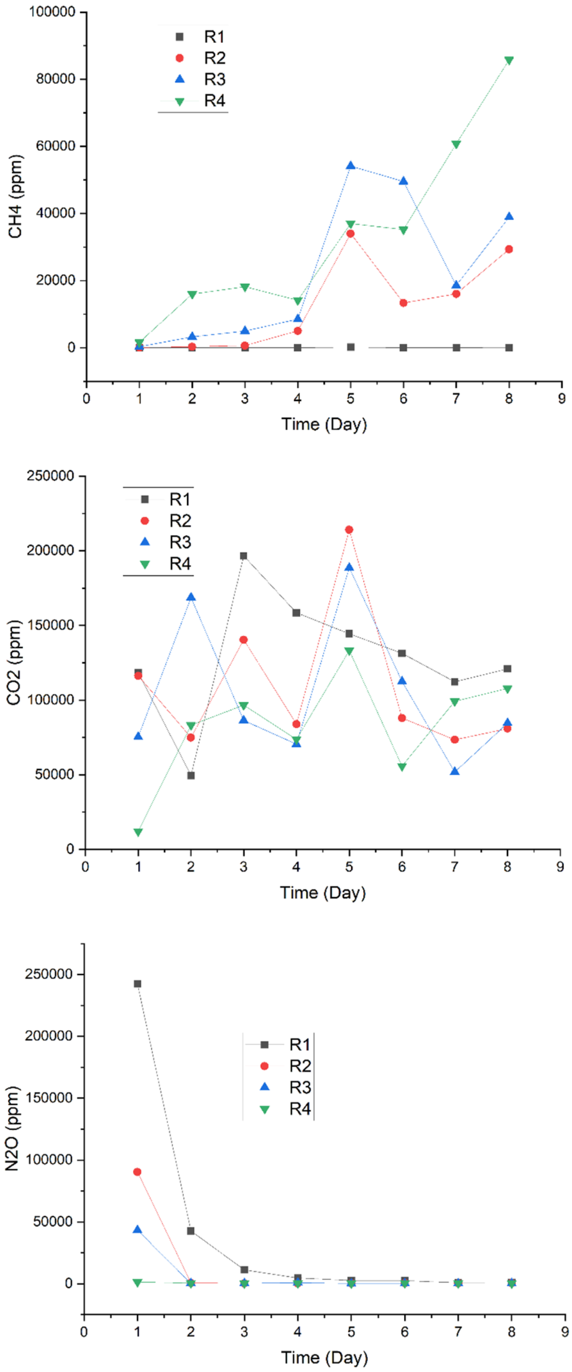

Figure 7. (a) CH_4 production, (b) CO_2 production, (c) N_2O production by MFCs biodigester

in the second week at 81.64%, while in the same week, reactors R1, R2, and R3 and CH_4 percentages of 0.02%, 1.68%, and 16.66%, respectively.

These results underscore the potential of cow manure in biogas production, surpassing the performance of pure vegetable waste. The biogas percentage in R1, from the first to the 8th week, remained relatively stable, ranging from 0.02% to 0.13% and finally reaching 0.29%. In contrast, R4, which utilized 100% cow manure, saw a significant increase in biogas percentage, ranging from 29.53% to 81.64%. The trend in the rate of biogas in R4 decreased from the first week to the fifth week, followed by an increase leading to the 8th week. These findings open up new possibilities for the co-digestion of cow manure with other organic materials, such as cow urine, food industry by-products, and cottonseed hulls, to significantly increase methane production (Thakur et al., 2023). It's important to note that cow manure possesses a balanced C/N ratio, facilitating the growth of methanogenic microorganisms that efficiently produce CH4. The physicochemical characteristics of cow manure, including dry matter content, carbon-to-nitrogen ratio, and chemical oxygen demand, play pivotal roles in enhancing the efficiency of biogas production. Understanding and optimising these factors can significantly improve biogas production processes (Saha & Mondal, 2023).

Previous research has explored the co-digestion of food waste with cow manure in AD to produce biogas. Cow manure alone (100%) produces 67.2% biogas, outperforming a mixture of cow manure (95%) and food waste by 53.9% on day 26 (Hilmi et al., 2023). The methane concentration, ranging from 54% to 69%, aligns with the typical methane content in biogas, indicating the effectiveness of AD using cow manure (Torbira & Saturday, 2021). According to Juntupally et al. (2024), biogas generated from organic waste generally consists of 55% to 60% methane (CH_4), 30% to 35% CO_2, and other minor gases such as hydrogen sulfide (H_2S), nitrogen, ammonia (NH_3), which are considered impurities. Previous studies have shown varying yields of CH_4, but achieving 90% of CH_4 content in biogas remains a significant challenge (Juntupally et al., 2024).

CO_2 production should be minimised because CO_2 gas causes global warming, decreases air quality, impacts health, and increases acidity in water environments such as rivers, lakes, and seas (Sarangi, 2023). The research results show that CO_2 in R4 was initially the lowest among the other reactors, starting at 10,506.94 ppm. Compared to the different reactors, R4 consistently produced lower CO_2 levels. The lowest average CO_2 gas concentration was 19.28% in R4, which contained 100% cow manure. Meanwhile, the highest CO_2 concentration was 30.98% in R1, which included 100% vegetable waste. In R1, the microbial community composition converts organic matter into CO2 more efficiently.

Microbial community structure plays a vital role in higher CO_2 production due to increased bacterial diversity (Stegenta-Dąbrowska et al., 2019). CO_2 gas production occurs throughout several stages of the AD process, from the breakdown of complex organic compounds to the formation of methane gas. In hydrolysis, some CO_2 can be produced as a byproduct of the breakdown of complex organic compounds into simpler forms. CO_2 is also produced as a byproduct of anaerobic metabolism by bacteria that produce organic acids during the acidogenesis stage. In the acetogenesis stage, CO_2 production results from the decarboxylation of organic acids. Finally, during the methanogenesis stage, CO_2 is produced as a byproduct of redox reactions, especially from reducing CO_2 to methane.

N_2O production in biodigester-MFCs

Nitrous oxide (N_2O) has significant environmental impacts, being a powerful greenhouse gas and a major contributor to the greenhouse effect (Dasti et al., 2021; Liu et al., 2022). Biodigester MFCs produce N_2O gas. The research results show that initially, R1 produced the highest N_2O levels, followed by R2, R3, and R4. All reactors significantly reduced N_2O production from week 2 to week 8 (see Figure 7c).

The maximum N_2O level was 242,221.80 ppb, produced by R1 in the first week. During the same week, R2, R3, and R4 produced N_2O at 90,410 ppb, 43,265 ppb, and 1,485 ppb, respectively. The lowest N_2O concentration was made by R3 in the fifth week, at 282.75 ppb. Overall, the average N_2O gas emissions were highest from R1 at 38,497.9 ppb, followed by R2 at 11,658.4 ppb, R3 at 5,792.0 ppb, and R4 at 547.3 ppb. These results indicate that more food waste leads to more significant N_2O emissions. The N_2O gas concentration pattern from the first week to the eighth week in both reactors 1, 2, 3, and 4 showed a general decrease. Microbiological activity plays an essential role in N_2O gas emissions during the anaerobic decomposition process (Pasvadoglou et al., 2023). N_2O emissions mainly result from the nitrification process (Shen et al., 2014). Substrate composition, nitrogen availability, and temperature influence N_2O emissions. Low oxygen levels during nitrification and inadequate C/N ratio during the denitrification process contribute to high N_2O emissions (Stenström et al., 2013). The C/N ratio of the substrate influences N_2O production: a higher C/N ratio causes a decrease in N_2O emissions due to increased denitrification processes (Yan et al., 2017).

CONCLUSIONS

An integrated system of AD was influenced by the variation of substrate composition of organic waste, as we found from the research results that a composition of 25% cow manure to 75% vegetable waste produced the most significant volume of biogas. We highlight that adding cow manure to vegetable waste can enhance biogas production and maximise electricity production while managing greenhouse gas emissions in sustainable energy systems. Within the integrated AD system from portable biodigester-MFCs, methane (CH_4) generation increased over time, peaking during the fifth and sixth and potentially continuing to rise until the eighth week from the cow manure. Meanwhile, vegetable waste alone produced the highest N2O levels, decreasing from the first week to the eighth week. To enhance the efficiency of this integrated system, appropriate strategies need to be implemented to increase the electrode surface area and improve the electron transfer in MFCs, thereby producing a more significant electric current. We found the optimal substrate to generate electricity and produce biogas in small but easily implemented portable biodigester-MFCs, a reactor with a 50%:50% ratio of vegetable waste and cow manure. The highest voltage was observed from the third reactor, with 50% cow manure and 50% vegetable waste on day 18, reaching 0.62 mV. This paper supports practical evidence of the potential application of portable biodigester-MFCs in generating electricity and biogas and reducing organic waste from the bottom level, such as in the household. It shows the promise of a green future and economic benefits in developing countries as households can use the reactor efficiently as part of actors in sustainable development.

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