Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.cbiore.id

Research Article

Optimizing aeration rates via bio-methane potential test for enhanced biodrying efficiency of refuse-derived fuel-3

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Abstract. Aeration forms a critical part of the biodrying of refuse-derived fuel-3 (RDF-3) and significantly affects the fuel's energy potential. Understanding the organic content (OC) of RDF-3 is crucial for determining the optimal aeration strategy. In this study, we conducted a bio-methane potential (BMP) test to estimate the OC by observing the conversion of organic matter into methane (CH_4) and carbon dioxide (CO_2). The observation of BMP was conducted using anaerobic digestion approach where substrate and inoculum are important parameters considered for the success of this test. Various ratios substrate-to-inoculum (S/I) were explored to assess their impact on biogas production, our research involved testing four S/I ratios (0.25, 0.5, 1.0, and 1.5) focusing on identifying the optimal aeration strategy. Based on stoichiometric calculations, the sample's biogas yield per gram volatile solid indicates RDF-3's OC is 1.5%. This OC value played a role in establishing the appropriate aeration rate (AR) for the biodrying process, which was determined to be 0.6 m^3/kg.day, indicating the action of effective microbial degradation processes. Ensuring the correct AR is vital for maximizing the energy potential of RDF-3. Implementing optimized aeration rates based on the BMP test in waste management practices can significantly improve RDF-3 biodrying efficiency. This approach enhances RDF quality, reduces moisture, increases calorific value, and minimizes greenhouse gas emissions, leading to more sustainable and efficient waste-to-energy conversion.

Keywords: Waste-to-Energy Conversion, Refuse-Derived Fuel Enhancement, Energy Recovery Optimization, Waste Treatment Technology, Waste Valorization

Received: 26th May 2024; Revised: 6th July 2024; Accepted: 5th August 2024, Available online: 12th August 2024

1. Introduction

At present, inappropriate waste management remains a widespread issue in many developing countries. The lack of adequate infrastructure poses a significant challenge, leading to increases in open dumping and uncontrolled burning of municipal solid waste (MSW) (Eguchi *et al.,* 2013; Ferronato & Torretta, 2019; Shovon *et al.,* 2024). Therefore, adopting sustainable waste processing practices is essential to reduce the risks arising from improper waste management. The development of innovative technologies to achieve sustainable waste processing goals will be an important future trend. Waste can be reused for various purposes, including the most intensive application of waste-to-energy (WtE) conversion (Asian Development Bank 2020). Refused-derived fuel (RDF) is an alternative fuel source obtained from waste processing in the form of segregated combustible material. The use of RDF forms an important step toward realizing sustainable energy recovery by applying WtE conversion that can then be used in combustion processes in the energy sector (Rahman *et al.,* 2015; Sagala *et al.,* 2018; Zieri & Ismail, 2019). There are seven types of RDF based on the density of the fuel and how it is processed (Kerdsuwan *et al.,* 2016). Among these, the most common types used in Thai industries are RDF-2 and RDF-3 (Itsarathorn *et al.,* 2022).

RDF-2 and RDF-3 are used in the cement industry and power plants in Thailand because the components of these fuels are obtained from segregated waste through mechanical separation (Itsarathorn *et al.,* 2022; Payomthip *et al.,* 2020), consist of combustible material, and can be treated to increase their low heating value (LHV). RDF-3 is composed of shredded waste with a size below 2 inches with relatively low density (Kerdsuwan *et al.,* 2016). However, the separation process still leaves a small component of organic compounds in RDF-3, which are likely derived from food waste contamination in dump sites. This organic content causes RDF-3 to have a relatively high moisture content (MC). These remnant organic compounds lead to humidity, which promotes the growth of microorganisms (Malinowski & Wolny-Koładka, 2017) and results in a low calorific value of RDF-3. Therefore, it is

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https://doi.org/10.61435/ijred.2024.60361
ISSN: 2252-4940/© 2024.The Author(s). Published by CBIORE

necessary to use technological solutions to enhance the quality of RDF-3 to suit combustion applications that require fuel quality comparable to conventional fuel.

Biodrying (biological drying) is an alternative bioconversion process used to treat waste with a high MC (Payomthip *et al.,* 2022a). Biodrying is commonly applied to various types of waste, including MSW, sewage sludge, manure, food waste, and biomass, to produce processed waste or RDF (Septiariva *et al.,* 2022; Ulhasanah *et al.,* 2022). Microorganisms in the waste assist in this bioconversion process under aerobic conditions (i.e., aerobic degradation). Therefore, adequate aeration supply is crucial for promoting the microorganisms' respiration, thereby degrading the organic matter in the waste (de Guardia *et al.,* 2008; Li *et al.,* 2022). In turn, this can ensure enhanced biodrying performance to achieve final treated waste products with high LHVs (Payomthip *et al.,* 2022a). The amount of aeration applied to the system depends upon the amount of organic content (OC) present in the material being dried. Biodrying has been applied in several previous studies; for example, Payomthip *et al.* (2020) evaluated shredded waste and achieved a 42.75% LHV increase through the application of a negative ventilation system. Furthermore, Ngamket *et al.* (2021) evaluated biodrying on MSW through a greenhouse solar radiation system with active and passive aeration and achieved a final LHV of 6,134.75 kcal/kg compared to an initial LHV of 1,688.55 kcal/kg.

However, determining the appropriate amount of aeration required for the biodrying of RDF-3 is challenging due to its relatively low OC. One method of determining OC in solid waste is by assessing the respiration index of the microorganisms involved in the degradation of organic material. By using anaerobic digestion approach, RDF-3 was tested to determine the amount of OC capable of producing biogas. The anaerobic test 4 (AT4) is used in solid waste management under anaerobic conditions, and previous studies have indicated that this test is a reliable method to assess the stability of composted sewage sludge during the maturation process, offering valuable information on the degree of stabilization and potential biogas formation (Bożym & Siemiątkowski, 2018; Bożym & Siemiątkowski, 2019). The AT4 method follows a similar principle to the bio-methane potential (BMP) approach, which involves evaluating the potential for biogas formation through the degradation of organic matter. Both of AT4 and BMP are helps determine the biodegradability and potential energy recovery from the waste material (Sidełko *et al.,* 2017; Bernat *el al.,* 2022). In the present study, BMP analysis was chosen due to the availability of suitable equipment and reactors.

By using a BMP assessment method based on the principle of anaerobic digestion (AD), RDF-3 was tested to determine the amount of OC capable of producing biogas. The most common biogases in the AD process are methane (CH_4) and carbon dioxide (CO_2). Ahmed *et al.* (2024) investigated the potential for biogas formation through anaerobic co-digestion in a mixture of sewage sludge and rise straw. Their results obtained the most dominant biogas composition was CH_4 of 60–70%, then CO_2 of 25–30%, and the remaining small part was H_2S concentration. Furthermore, Clagnan *et al.* (2023) evaluated the effect of microbial acclimatization in the formation of biogas from three different materials (bioplastics, starch-based and polylactic-acid). The percentage of CH_4 and CO_2 production was varies depending on the type of substrate used. However, a key point from these relevant studies is that anaerobic digestion consistently determines the potential for biogas formation, especially methane. Based on the amount of these biogases formed, the amount of decomposing organic matter present in the RDF-3 can be calculated using the reaction equation and the moles of each compound (Mekonen *et al.,* 2023). This approach presents a challenge in estimating the biodegradation of organic-based matter under aeration as degradation in AD and degradation by biodrying aeration occur under different conditions, which can be explained by the molecules that make up the organic materials. Therefore, this study aims to determine the amount of OC successfully degraded during the BMP process. After the OC obtained from the feedstock used, RDF-3 as substrate, the next step in continuous experiments was determine the estimated aeration supply to help counted-OC biodegradation. The CH_4 and CO_2 formed during the process were also measured to determine the optimal aeration rate for biodrying RDF-3.

2. Methodology

2.1 Feedstock Preparation

2.1.1. Inoculum

The inoculum used in this study was anaerobic sludge obtained from the up-flow anaerobic sludge blanket (UASB) of brewing process sludge from Pathum Brewery Company Limited, Thailand. UASB was selected as the inoculum in this study because the BMP process occurs anaerobically. Asato *et al.* (2016) also used this type of inoculum, which drives CH_4 production. The inoculum, taken from wastewater treatment, was subsequently stored in a refrigerator at 1–4 °C. This temperature range can inhibit the activity of microorganisms. In storage, the microorganisms should not be active to prevent outset degradation and free CH_4 gas formation. The sludge was activated using a glucose sugar solution to ensure its suitability for use as an inoculum. Glucose is a common nutrient that is easily metabolized by almost all microorganisms to increase respiration (Izadi & Andalib, 2023), and this type of simple sugar is readily degraded (Alonso-Riaño *et al.,* 2024). The sugar solution used as an activator had a concentration of 1% (1:100 w/v), which was chosen to ensure it did not affect the pH of the sludge (Mangas *et al.,* 2023; Voegeli *et al.,* 2014). The activation was performed for seven days in an incubator under mesophilic temperature conditions (37 °C). This method has been previously conducted by Ohemeng-Ntiamoah & Datta (2019), who also performed pre-incubation of UASB brewery sludge at moderate temperatures to optimize microbial activity during the BMP process in the reactor. Another study was conducted by Elbeshbishy *et al.* (2012), in which pre-incubation of food waste and primary sludge was performed at 37 °C for 21 days. The time chosen for activation depends on the nature of the sludge characterization, with the most similar previous studies chosen as references.

2.1.2. Substrate

The substrate used in this study was RDF-3 obtained from the On Nut Waste Transfer Station, Bangkok, Thailand. The initial size of RDF-3 was 2 inches. However, solid samples for BMP analysis should be less than 10 mm in size to achieve faster conversion rates when conducting the BMP process (Ohemeng-Ntiamoah & Datta, 2019). The substrate was prepared by cutting the RDF-3 into smaller pieces to reduce the particle size before adding it to the system. There was no special treatment in terms of storing the raw substrate materials because the fresh RDF-3 was processed immediately after it was obtained.

2.1.3. Substrate concentration and inoculum ratio (S/I)

The substrate-to-inoculum ratio (S/I) describes the concentration of the substrate, in the form of volatile solids (VS), and the inoculum, in the form of volatile suspended solids (VSS).

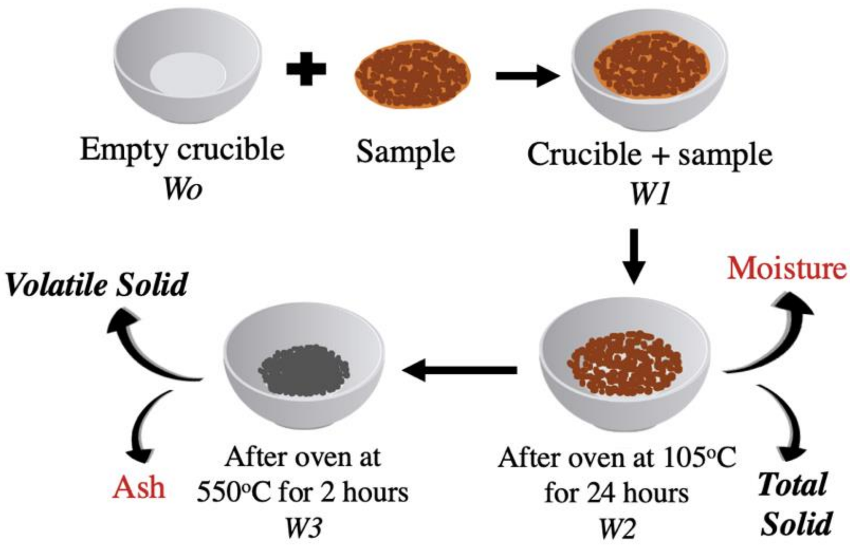

Fig 1 Pathways of characterization total solid and volatile solid

Four S/I variations were used in this study (0.25, 0.5, 1.0, and 1.5). The S/I variations used in this research relate to the VS and VSS values obtained from substrate and inoculum characterization. Several previous studies have reported that the optimum substrate concentrations for AD are in the range of 2–100 g VS/L, with an inoculum concentration of 10 g VSS/L (Asato *et al.,* 2016; Ohemeng-Ntiamoah & Datta, 2019; Yan *et al.,* 2018). These ratios were achieved using a constant inoculum loading rate, while the substrate concentration was varied. This aims to assess the ability of microorganisms to degrade different amounts of substrate under the same conditions. The inoculum concentration used was 10 g VSS/L; this value was adopted from Ohemeng-Ntiamoah & Datta (2019), who reported that optimal biogas production occurred using S/I ratios based on an inoculum concentration of 10 g VSS/L. Based on the predetermined S/I values and with a fixed inoculum concentration, the substrate concentrations used were 2.5 g VS/L, 5 g VS/L, 10 g VS/L, and 15 g VS/L.

2.2 Experimental Setup and Monitoring

2.2.1. Analytical technique

During the BMP experiment, the VS parameter was used to characterize the substrate, while the VSS parameter was used to characterize the inoculum. A mass of 1.5 g of RDF-3 was used to determine the VS, and 3 mL of sludge was used to determine the VSS. A schematic of the pathways used to measure VS is shown in Figure 1.

2.2.2. Reactor design and setup

The reactor used in this study was a 100 mL glass vial bottle, with a rubber and aluminum cap installed tightly to prevent free air from entering the reactor system. The working volume was 50 mL, with the remaining 50 mL used as headspace to accommodate the gas formed. The experiments were performed using the four S/I ratios described above, each with three replicates, and one sample was used as a control. The control sample contained sludge and distilled water with no substrate to compare the final CH_4 yield with those obtained from substrate degradation. The other samples contained substrate, inoculum, and deionized (DI) water, which were used to make a slurry. After the slurry was added to the reactor, CO_2/N_2 gas was applied at a pressure of 1 atm to remove the remaining oxygen (O_2) and ensure anaerobic conditions within the reactor. The samples were placed in an incubator under mesophilic conditions at 37 °C for a total incubation time of 30 days.

2.2.3. Gas measurement

The biogas volume was measured daily for the first 10 days and analyzed using a Shimadzu GC-2014 gas chromatograph. The

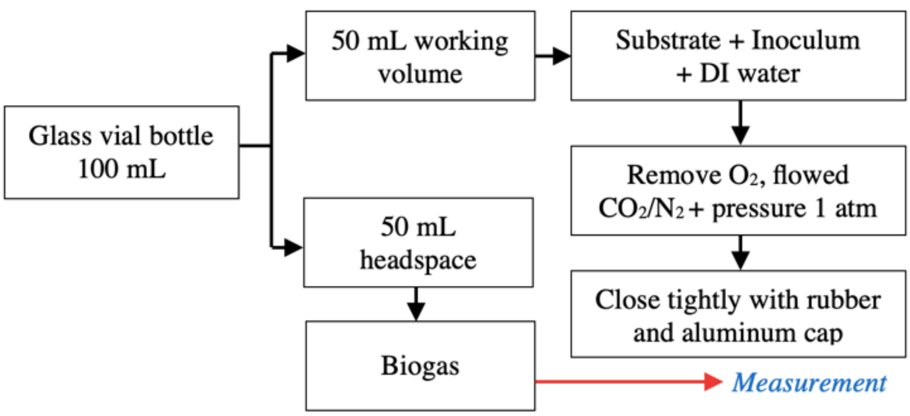

Fig 2 Reactor setup diagram flow

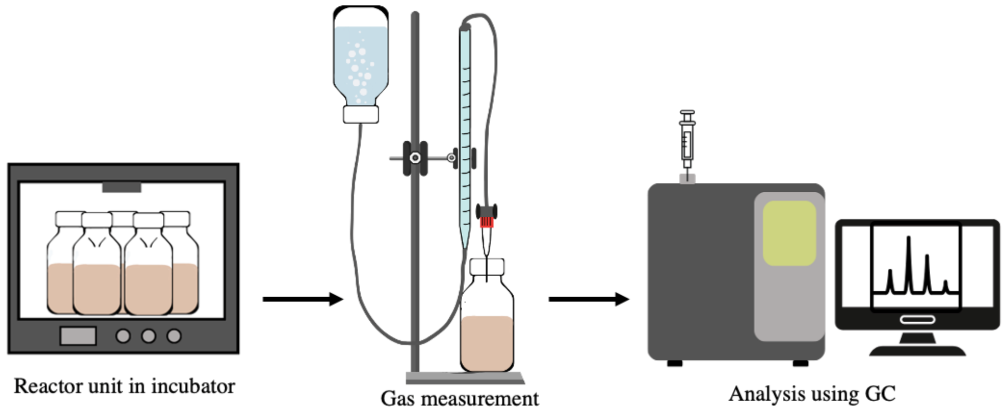

Fig 3 Schematic design of monitoring biogas through BMP

gas volume was measured using a liquid displacement technique in which the liquid volume decreased by an equivalent amount to the volume of gas produced (Shitophyta *et al.,* 2020). When the biogas generation decreased after the initial 10 days, measurements were then conducted every five days during the remaining 20 days of the experiment. Gas chromatography analysis aims to determine the components of the obtained biogas and their concentrations. The method used in this study was adopted from Manthos *et al.* (2023). A schematic of the experimental design setup is shown in Figure 3.

2.2.4. Organic matter analysis

The aeration supply required for biodrying was estimated based on how much organic matter was present in the RDF-3. Since the OC cannot be physically separated by hand, the OC is measured based on the CH_4 and CO_2 formed during the BMP process. There are four stages of biogas formation in the AD process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Mekonen *et al.,* 2023; Voegeli *et al.,* 2014). The overall reaction equations are as follows:

Hydrolysis

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$
$$\frac{1}{2}C_{12}H_{22}O_{11} + \frac{1}{2}H_2O \rightarrow C_6H_{12}O_6 \quad (2)$$

Acidogenesis

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (3)$$
$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (4)$$
$$C_6H_{12}O_6 + \frac{3}{2}O_2 \rightarrow 3CH_3OH + 3CO_2 \quad (5)$$

Acetogenesis

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (6)$$
$$CH_3CH_2OH + 2H_2O \rightarrow CH_3COOH + 3H_2 \quad (7)$$

Methanogenesis

$$CH_3COOH \rightarrow CH_4(g) + CO_2(g) \quad (8)$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (9)$$
$$4CH_3OH + 6H_2 \rightarrow 3CH_4(g) + 2H_2O(g) \quad (10)$$

The gas volume obtained was then used to calculate the moles of each compound in the measured gas. This method followed the basic laws of chemistry and the ideal gas law. The gas volume was converted to mol using the following equation:

$$PV = nRT \quad (11)$$

where P is pressure (atm), V is the volume of gas (L), n is mole (mol), R is the ideal gas constant 0.082 (L atm/K mol), and T is temperature in kelvin (K).

2.2.5. Aeration rate determination

To determine the final result, the steps must be taken in the following:

$$O_2 \text{ demand} = \text{mass of } O_2 \text{ x mass of organic} \quad (12)$$

O_2 demand is an estimation of the total O_2 required by microbes for degraded organic fraction. Where, mass of organic is the mass obtained from conversion mole calculation gained from this BMP test.

$$\text{Air demand} = \frac{O_2 \text{ demand}}{O_2 \text{ in the air}} \quad (13)$$

Air demand refers to the air required to dry organic fraction being processed effectively. Where O_2 in the air is 0.232.

$$\text{Air volume} = \frac{\text{air demand}}{\text{air density}} \quad (14)$$

Air volume refers to the total amount of air filled and flowed into the reactor system, with the air density is 1.2 m^3/kg.

$$\text{Aeration rate} = \frac{\text{total mass}}{\text{air volume per day}} \quad (15)$$

Aeration rate is the rate of air flowed into the system in kilogram total mass loaded per day. The volume use in Eq (15) is come from air volume from Eq (14) divided by total days during the biodrying process.

2.3 Statistical method

Replicate in each S/I trials were producing biogas with different volume obtained. As a final value from each trial need a single amount, the statistical using was mean value and standard deviation of sample.

3. Results and Discussion

3.1 Substrate and Inoculum Characterization

Physical characterization was conducted to determine the proportions of substrate and inoculum, which are measured

Table 1
Characterization of inoculum

No	Mass of crucible (g)	Initial sludge (mL)	Mass after dry 105°C (g)	Mass after furnace (g)	% TSS wb	% VSS wb	%VSS db
1	18.6324	4	18.7916	18.6535	3.83	3.4525	90.14
2	19.7221	3	19.8360	19.7341	3.79	3.3966	89.46
3	18.8176	3	18.9349	18.8303	3.91	3.4866	89.17

Table 2
Characterization of substrate

No	Mass of crucible (g)	RDF 3 (g)	RDF + crucible (g)	RDF-3 after dry 105°C (g)	Mass after furnace (g)	% TS wb	% VS wb	%VS db
1	20.1098	1.5313	21.6411	21.0852	20.2289	63.697	55.919	87.789
2	19.9483	1.5014	21.4497	20.8886	20.0604	62.628	55.161	88.078
3	18.1824	1.5221	19.7045	19.1328	18.2927	62.440	55.193	88.394

using the VS and VSS parameters, respectively, in the BMP process. The results of the inoculum characterization are presented in Table 1, and the substrate characterization is presented in Table 2.

The obtained characterization results showed that the average wet basis (wb) inoculum concentration was 3.44%. This concentration requires 14.5 mL of sludge to achieve 10 g VSS/L. For the substrate shown in Table 2, the average VS of the substrate was 0.8415 g, which contained 1.5 g RDF-3. Based on this VS information, to achieve the target S/I ratios of 0.25, 0.5, 1.0, and 1.5, the corresponding reactions contained 0.2225 g, 0.445 g, 0.89 g, and 1.335 g of substrate, respectively.

Various S/I were tested to determine their impact on biogas production. This ration was effective in balancing microbial activity and substrate availability. The optimal S/I ration enhances biogas production.

3.2 Biogas Production

3.2.1. Methane generation

The four S/I ratios exhibited varying CH_4 gas formation, where higher S/I ratios produce more CH_4. The total CH_4 yields in the present study for S/I ratios of 0.25, 0.5, 1.0, and 1.5 were 11.6 mL, 30.7 mL, 51.8 mL, and 86.9 mL, respectively. The CH_4 production trends are shown in Figure 4.

Increasing the substrate concentration in the reactor yielded higher CH_4 production. The factors that influence CH_4 production in AD are the amount of organic content present in the material, which relates to the substrate concentration (Ali *et al.,* 2024; Wang *et al.,* 2015), the activity of degrading microorganisms, which can be promoted through the addition of an appropriate inoculum (Elbeshbishy *et al.,* 2012; Koch *et al.,* 2017), and ensuring the environmental pH remains within a

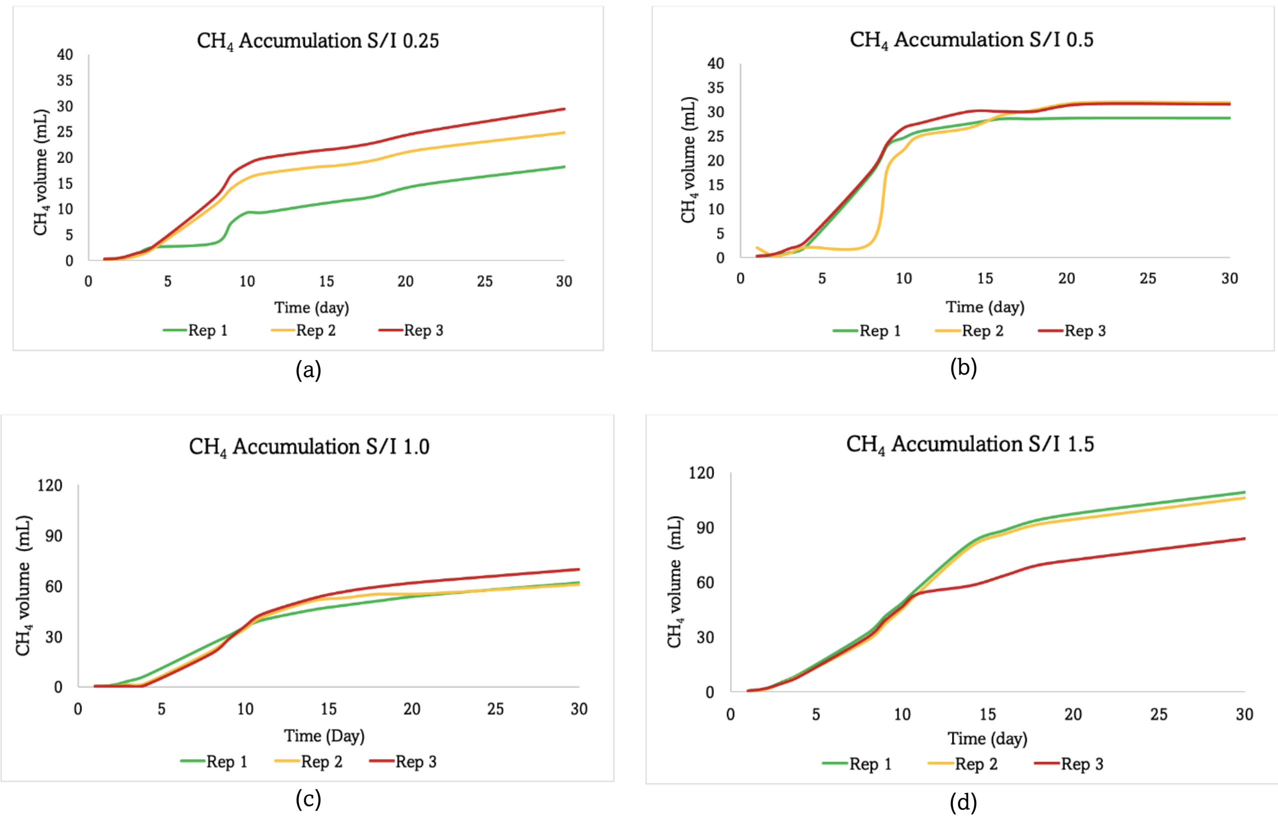

Fig 4 CH_4 accumulation of (a) S/I 0.25, (b) S/I 0.5, (c) S/I 1.0, and (d) S/I 1.5

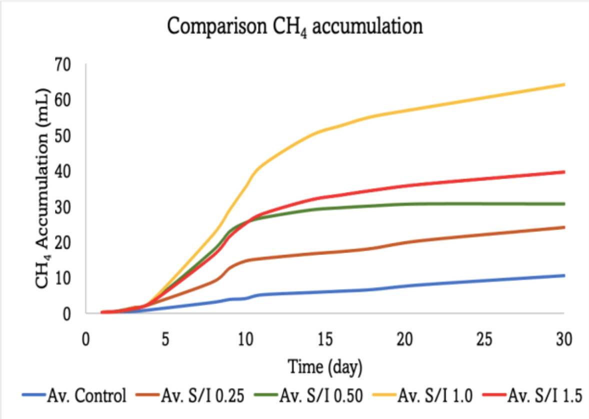

Fig 5 CH_4 accumulation in each replicate

range suitable for an anaerobic bacterial environment (6.5–7.5) (Voegeli *et al.,* 2014). This is attributed to the greater availability of food (i.e., the OC) for the same number of microorganisms.

A study by Wang *et al.* (2015) showed that increasing the substrate concentration of soymilk and sugar from 2 g VS/L to 6 g VS/L caused a 30% increase in CH_4 potential. Furthermore, Yan *et al.* (2018) conducted studies on the co-digestion of chicken manure and corn, with a 25% increase in CH_4 gas accumulation reported when the substrate concentration was increased. In contrast, Gaur and Suthar (2017) added various inocula to drive bio-methanation and reported that the use of a 1:1 ratio of substrate to inoculum achieved the optimum conditions for biomethane production.

In the present study, the amount of CH_4 produced in each reactor with varying amounts of substrate was only used to determine how fast the AD process takes place at the appropriate S/I composition. The potential to produce CH_4 per gram of VS material is calculated based on an average. The average CH_4 yield in this BMP experiment was 5.2 ± 0.82 mL/g VS, i.e., 1.7825 g RDF-3 produces 5.2 mL CH_4 on average over 30 days. This result is relatively small compared with the findings of Kawai *et al.* (2014), who found that the highest CH_4 production from food waste reached 435 mL/g VS with an S/I ratio of 3.0. This difference is expected as the substrate used here, RDF-3, is composed of dominantly inorganic shredded material from the combustible waste fraction with only a small component of organic content. A comparison between CH_4 accumulation in each concentration is shown in Figure 5.

Based on the reports of several studies, CH_4 gas accumulation depends on the amount of OC loaded into the reactor during the BMP process. However, there was a discrepancy in the results of this study. In Figure 4, trial S/I 1.5, with the highest substrate concentration, produced less CH_4 than the S/I 1.0 trial. There are several potential explanations for this phenomenon. (i) The components of the organic substances in the samples may have differed. Organic matter consists of complex macromolecules of organic substances, including carbohydrates, protein, and fat. Trial S/I 1.5, with low CH_4 production, may have contained a higher proportion of lignocellulose. Induchoodan *et al.* (2022) reported that complex macromolecules consisting of more lignocellulose are more difficult to break down than other types of complex macromolecules, leading to a lower degradation rate of this OC type. (ii) The sample used in this trial may have contained excessive carbohydrates, which caused significant volatile fatty acid (VFA) accumulation during the acidogenesis stage. The acidogenesis phase occurs faster than other phases in AD (Induchoodan *et al.,* 2022). Excess VFA accumulation may have led to a drop in pH, which would have in turn inhibited methanogenic bacterial activity (van Lier *et al.,* 2008). Notably, the final pH measured in this trial was 6, in contrast to a value of 7 measured in the other trials. (iii) Trial S/I 1.5 may have contained a toxicant that inhibits methane production. The most common types of gas in solid waste that can become toxicants in the AD process include ammonia, free CH_4, and hydrogen sulfide (H_2S) (Ko *et al.,* 2015; Romero-Güiza *et al.,* 2016; Kang *et al.,* 2020). Romero-Güiza *et al.* (2016) reported that bioaugmentation via the introduction of additional enzymes helped to overcome the presence of toxicants in the AD process. Their study reported that the introduction of this additive led to increased methanogenic and hydrolytic activity, resulting in increased waste solubilization. In the present study, toxicants may be present in the samples because RDF-3 is produced from solid waste, which has the potential to emit the gases mentioned above.

Additionally, variations in the total solid (TS) content in the OC could influence the results. This variability may occur because RDF-3 is derived from solid waste, and the OC composition varies among different types of solid waste. Wang *et al.* (2023) reported that TS content values in the substrate may differ slightly when using organic waste as substrate. This results in mass transfer limitations between microbes and substrate—this reduces the availability of nutrients for microorganisms, adversely impacts their metabolisms, and, ultimately, results in decreased degradation of VS and lower biogas production.

3.2.2. CO_2 generation

The trends in CO_2 concentration are expected to be the inverse of those observed in terms of CH_4 production, i.e., increased CH_4 yields lead to less CO_2 production. The optimum conditions for AD occur in a thermophilic environment. The absence of O_2 in the reactor's environment suppresses the growth of anaerobic bacteria, leading to CH_4 production (Papa *et al.,* 2023). At the beginning of the digestive process, between days 5 and 10, CO_2 production reaches its peak. The CO_2 gas accumulation graph is shown in Figure 6. However, in contrast to expectations, the observed behavior of CO_2 gas formation at varying S/I ratios was the same as that of CH_4 gas, i.e., CO_2 production increased with increasing substrate concentration. The 13 gas volume measurements obtained over 30 days from each experimental replicate are presented in Table 3.

Table 3 shows that the average accumulated net volumes per sample for S/I ratios of 0.25, 0.5, 1.0, and 1.5 were 6.9, 9.9, 25.6, and 46.5 mL, respectively (in terms of concentration ratio). This volume was then divided by the substrate concentration in each experiment, resulting in net

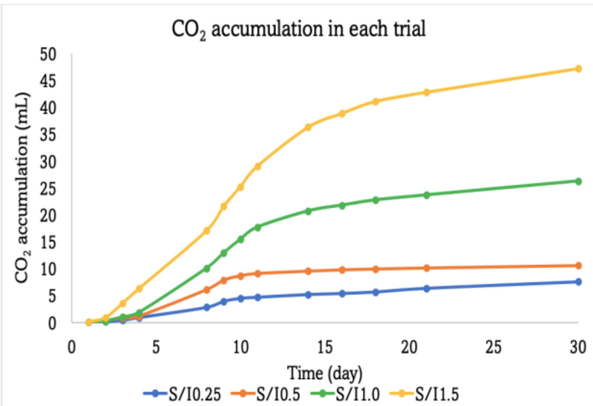

Fig 6 CO_2 accumulation in each replicate

Table 3
CO_2 production in each replicate

S/I 0.25									**CO_2 (mL)**							
Measuring No.		1	2	3	4	5	6	7	8	9	10	11	12	13	Accumulation	Vol control
	Rep1	0.1	0.1	0.2	0.5	0.3	1.1	0.6	0.0	0.5	0.3	0.3	0.7	1.1	5.7 ± 0.35	
	Rep2	0.1	0.1	0.3	0.5	2.6	0.9	0.6	0.3	0.4	0.2	0.3	0.6	1.1	7.9 ± 0.66	
	Rep3	0.1	0.1	0.4	0.4	2.8	1.3	0.6	0.3	0.5	0.2	0.3	0.6	1.4	9.1 ± 0.75	0.7
Average															7.6 ± 1.72	
Net volume															**6.9**	
S/I 0.5									**CO_2 (mL)**							
Measuring No.		1	2	3	4	5	6	7	8	9	10	11	12	13	Accumulation	Vol control
	Rep1	0.1	0.1	0.3	0.6	4.9	2.0	0.5	0.4	0.5	0.4	0.0	0.1	0.0	9.8 ± 1.35	
	Rep2	0.1	0.3	0.7	0.4	5.0	1.3	1.0	0.5	0.8	0.4	0.5	0.0	1.4	12.3 ± 1.29	
	Rep3	0.1	0.2	0.6	0.0	4.8	2.0	1.0	0.3	0.0	0.0	0.0	0.5	0.0	9.6 ± 1.35	0.7
Average															10.6 ± 1.50	
Net volume															**9.9**	
S/I 1.0									**CO_2 (mL)**							
Measuring No.		1	2	3	4	5	6	7	8	9	10	11	12	13	Accumulation	Vol control
	Rep1	0.1	0.3	1.8	1.8	8.6	1.9	2.1	1.5	2.3	1.1	1.0	1.5	2.9	26.9 ± 2.10	
	Rep2	0.1	0.1	0.5	0.4	8.4	3.1	2.5	2.6	3.5	0.7	0.8	0.1	2.2	24.9 ± 2.30	
	Rep3	0.1	0.0	0.0	0.3	7.8	3.4	3.1	2.6	3.3	1.5	1.1	1.2	2.7	26.9 ± 2.15	0.7
Average															26.3 ± 1.15	
Net volume															**25.6**	
S/I 1.5									**CO_2 (mL)**							
Measuring No.		1	2	3	4	5	6	7	8	9	10	11	12	13	Accumulation	Vol control
	Rep1	0.2	0.7	3.0	3.0	11.3	4.6	3.5	3.9	9.5	2.8	2.3	1.9	4.6	51.2 ± 3.17	
	Rep2	0.1	0.6	2.6	2.7	9.9	4.2	3.9	4.1	10.5	2.8	2.2	1.7	4.6	49.9 ± 3.13	
	Rep3	0.1	0.9	2.4	2.7	11.2	4.7	3.7	3.4	1.8	2.1	2.2	1.5	4.1	40.5 ± 2.74	0.7
Average															47.2 ± 5.83	
Net volume															**46.5**	

volumes per gram of VS of 2.7 mL/gVS (S/I 0.25), 1.9 mL/gVS (S/I 0.5), 2.6 mL/gVS (S/I 1.0), and 3.1 mL/gVS (S/ I 1.5). These experiments showed that, on average, 2.6 mL of CO_2 was produced per gram of VS substrate. In total, 1.7825 g of RDF-3 was degraded to produce 2.6 ± 0.47 mL of CO_2.

3.3 Organic compound determination based on methane production.

3.3.1. Based on methane production

The CH_4 gas produced is converted according to the basic laws of chemistry. Accordingly, a stoichiometry reaction equation is used and solved based on balancing its coefficient. Considering the four stages of biogas formation, the stoichiometry of the organic compounds involved in the reaction can be calculated starting with the final stage of the reaction (methanogenesis) and working backward to the earliest stage (hydrolysis). BMP tests for 30 days demonstrated that 1.7825 grams of wet RDF-3 could produce 5.2 mL of CH_4 gas.

Based on the formula in Equation (11), the moles of CH_4 can be calculated as:

$$n = \frac{1\,atm \times 5.2\,mL}{0.082\,Latm/Kmol \times 310\,K} = 0.2\,mmol$$

This equation indicates that 0.2 mmol of CH_4 is produced for each mL/gVS of CH_4 gas. As noted above, the reaction stoichiometry is calculated "backward", starting from the methanogenesis process, based on the moles of CH_4 obtained. Methanogenesis forms the final step in biogas production and CH_4 formation (Mekonen *et al.,* 2023). The coefficients of the stoichiometric equation represent the number of moles of each substance (Ball, 2012). During methanogenesis, acetic acid (CH_3COOH) breaks down into CH_4 and CO_2 Based on Equation (8), the coefficients of CH_3COOH and CH_4 are the same (i.e., these substances react in a 1:1 molar ratio); therefore, the number of moles of CH_3COOH was the same as that of CH_4. In the acetogenesis stage, acetogenic bacteria convert long-chain fatty acids, VFAs, and alcohols into hydrogen, CO_2, and CH_3COOH (Voegeli *et al.,* 2014). Based on Equation (7), 0.2 mmol of ethanol was obtained. Subsequently, during the acidogenesis stage of biogas formation, acidogenic bacteria convert organic matter from simple sugar, CH_3COOH, and degraded fatty acid into acetate, CO_2, hydrogen (as VFA), and alcohol (Mekonen *et al.,* 2023; Voegeli *et al.,* 2014). Based on the reaction stoichiometry in Equation (3), the corresponding number of moles of glucose was 0.1 mmol. The final step is hydrolysis, in which complex polymers are transformed into smaller molecules in the presence of acidic catalysts. Generally, the macromolecule that decomposes and passes through the BMP process from organic substrates is cellulose, which represents the main component of plant cell walls. The stoichiometry of Equation (2) indicates that the molecular coefficient of the cellulose polymer is half that of glucose; accordingly, 0.05 mmol of cellulose was ultimately degraded into 0.2 mmol of CH_4.

3.3.2. Based on CO_2 production

In addition to CH_4, organic material degradation in AD results in CO_2 gas formation. In this case, the CO_2 production also describes the proportion of OC in the sample. Determining the amount of OC based on CO_2 results follows the same principles as determining the value based on CH_4. The chemical reaction for the formation of CO_2 gas from the methanogenesis process is as follows:

$$C_6H_{12}O_6 + 3CH_4 \rightarrow 3CO_2 \quad (12)$$

Based on Equation (12), 0.2 mmol of CO_2 formed as its coefficient is equal to that of CH_4. Comparing the coefficient reaction in Equation (2) indicates the final $C_{12}H_{12}O_{11}$ content is 0.03 mmol. Thus, 0.03 mmol of OC was degraded to CO_2 in this process. Based on the number of moles obtained, 17.1 mg of OC was degraded to CH_4 while 10.26 mg was degraded to CO_2. Accordingly, the total OC degraded during the BMP process was 27.36 mg per 1.7825 g wet RDF-3. So, the calculated OC was 1.5% contain in wet RDF-3, which is this value as a critical for determining the aeration rate needed for efficient biodrying.

The stoichiometric method, used to determine compounds and their masses, is widely applied and is not limited to the realm of chemistry. For example, Reichert and Schuwirth (2010) evaluated the derivation process of stoichiometry in environmental models. Their study presented a unified approach to characterize organic matter based on elemental mass fractions, organic carbon, or chemical O_2 demand. Along with the mathematical framework, their proposed framework can directly be used for the automatic calculation of stoichiometric coefficients in any environmental simulation and software. In addition, Ren *et al.,* (2023) also utilized stoichiometry to illustrate the elemental transformation and main product during the AD of food waste. Their stoichiometry assessment considered the lipid/TS ratio and microbial coefficient yield (MCY). Their study found that the lipid/TS ratio increases as the MCY decreases, leading to a positive effect on CH_4 conversion efficiency.

Furthermore, Xie *et al.* (2023) evaluated the biodegradability of dibutyl phthalate (DBP) and diethyl phthalate (DEP). Stoichiometry analysis was used to determine a biomass-based mass balance using a general biomass formula ($C_5H_7O_2N$), with the abundance of carbon recorded as 1.1/5 (DBP) and 3.3/5 (DEP). The output of their evaluation allowed the degradation reactions to be predicted, i.e., Equation (13) for DBP and Equation (14) for DEP.

$$C_{16}H_{22}O_4 + 15.98O_2 + 0.70NH_3 \rightarrow 0.70C_5H_7O_2N + 9.59H_2O + 12.48CO_2 \quad (13)$$

$$C_{12}H_{14}O_4 + 5.58O_2 + 1.58NH_3 \rightarrow 1.58C5H_7O_2N + 3.83H_2O + 4.08CO_2 \quad (14).$$

Overall, this review illustrates that stoichiometry is a highly reliable method for theoretical mass mapping and for predicting the occurrence of reactions.

3.4 Aeration rate determination based on the organic content

The OC results obtained above were then used to determine the appropriate aeration rate (AR) for the biodrying process. Biodrying was performed using three lysimeter reactors, each with a different loaded feedstock. The OC weights calculated from degradation during BMP was 27.36 mg OC per 1.7825 g wet RDF-3. Accordingly, the estimated organic mass values in each lysimeter were 663.5 g (lysimeter 1), 680.8 g (lysimeter 2), and 709.4 g (lysimeter 3). Determining the AR means supplying the O_2 needed to degrade the organic material. The chemical reaction equation that takes place in this process is:

$$C_{11}H_{22}O_{11} + 11O_2 \rightarrow 11CO_2 + 11H_2O \quad (15)$$

Based on these equations and almost the same amount of organic matter in each lysimeter, it was determined that all three lysimeters require an AR of 0.6 m^3/kg.day. This value was thus chosen as the highest AR value for biodrying. The three reactors each had a different AR, with values of 0.2, 0.4, and 0.6 m^3/kg.day chosen. The selection of these AR values was guided by previous studies of the biodrying of RDF, in which the AR was typically set within the range of 0.2–0.6 m^3/kg.day (Bhatsada *et al.,* 2022; Itsarathorn *et al.,* 2023).

Selecting a suitable AR value and applying it to the biodrying system plays a crucial role in achieving optimal biodrying performance (Yuan *et al.,* 2018; Park and Lee 2022; Li *et al.,* 2022). An adequate AR ensures the stability of the system's conditions during biodrying. The output from this process is RDF with an improved LHV, which can be more widely used for a range of applications. Payomthip *et al.* (2022b) reported that selecting an appropriate continuously supplied AR was able to remove more moisture and achieve a more homogeneous heat distribution in the biodrying system. The continuous airflow trial resulted in a product with an LHV of 4,938.0 kcal/kg and the lowest MC of 22.2%. In addition, Itsarathorn *et al.* (2023) reported the optimal AR supply in a biodrying system for wet RDF-2 was 0.6 m^3/kg.day. The final product in their study had an increased LHV of 4,496 kcal/kg compared to its initial value of 2,936 kcal/kg. Furthermore, as a comparison, Ngamket *et al.,* (2021) carried out biodrying without aeration supply (i.e., as a control system) in a greenhouse reactor. This trial achieved a high MC value of 30.51% compared to the trial with supplied aeration. Based on this review, supplementary aeration is required for effective biodrying. Supplying aeration helps to drive out water molecules from the feedstock and speeds up the evaporation process.

3.5 The role of implementing BMP in appropriate waste management

In many studies within this field, AD processes, analyzed through bio-methane production, have been applied to waste to generate biogas as an energy resource. Typically, these processes utilize waste with a high OC. However, anaerobic digestion via BMP is unfortunately unsuitable for large-scale industrial implementation. Nevertheless, the adoption of this technology yields positive impacts across various sectors, facilitating life cycle assessments within the food industry for processing expired food waste, the livestock industry, and household waste management (Ahire *et al.,* 2024; Keogh *et al.,* 2024; Nilsson Påledal *et al.,* 2018). A study by Ahire *et al.* (2024) evaluated biogas formation from expired grocery waste, i.e., vegetables and fruit, with varying organic content levels and moisture. From several experiments on expired food ingredients, mart expired waste was found to have the greatest potential for producing biogas, reaching 396 mL/gVS. This is because this waste contains a large amount of organic material, including proteins, fats, and carbohydrates, which were converted into volatile solids during the decomposition process and are responsible for the observed increase in biogas production.

Furthermore, Fernandes *et al.* (2023) evaluated the potential energy recovery from various kinds of cattle manure to produce biomethane. The greatest CH_4 production reached an LHV of 6,210.45 kJ/kg, which meets the Portugal's national biogas and biomethane requirements. Cattle manure has great potential for biomethane production through AD, which is feasible at 73.6% (Fernandes *et al.,* 2023). In addition, Keogh *et al.* (2024) evaluated the expansion of biomethane production from the AD process for use as a substitute for diesel in vehicles. Their results show that the use of biomethane can reduce greenhouse emissions from fossil fuels, with an emission reduction potential of 22.72–96.96 gCO2eq/MJ. The types of raw materials used in AD applications affect the LHV, ultimately influencing the extent to which emissions can be potentially mitigated (Keogh *et al.,* 2024). Based on several review studies mentioned, it was concluded that BMP assay is the most promising approach for promoting bioenergy recovery and realizing innovation in sustainable waste management.

Although the approach proposed in this study has important implications for the biodrying of RDF, a notable limitation of the approach used to estimate the AR is that the formula for the organic molecules that form OC in RDF-3 is only theoretical. This gap can be addressed through further research into the relationship between theoretical AD molecules and the actual organic molecules present in the feedstock used for biodrying.

4. Conclusion

The study into optimizing aeration for biodrying RDF-3 through BMP testing has yielded important insights into enhancing WtE conversion processes. Key findings demonstrate a direct correlation between increased AR values and biogas production, primarily CH_4, highlighting the key role of aeration in augmenting the biodrying efficiency of RDF-3. This research not only helps provide an improved understanding of the biodrying mechanism but also proposes a feasible method to boost the energy potential of RDF-3 as an efficient and sustainable fossil fuel alternative. The optimal aeration rate of 0.6 m^3/kg.day resulted in a notable CH_4 output increase of up to 30%. This highlights the potential efficiency gains in WtE applications. A systematic analysis of the effect of aeration on CH_4 yields provides a foundation for future studies to refine biodrying techniques, intending to achieve superior energy recovery. Future studies should assess the practically and scalability of these results across various waste management settings. Additionally, exploring the integration of real-time aeration control system and evaluating the optimized biodrying process in industrial applications will be essential. This research has a range of implications, providing key insights into waste management protocols and renewable energy production. This study aims to contribute to sustainable waste management solutions by improving the WtE process efficiency, in line with global sustainability targets. In summary, this research enriches the scientific understanding of biodrying and underscores its practical implications in enhancing WtE technologies.

Acknowledgments

The authors acknowledge the financial support from The Joint Graduate School of Energy and Environment (JGSEE). This study was supported by Center of Excellent on Energy Technology and Environment (CEE), King Mongkut's University of Technology Thonburi (KMUTT),

Author Contributions: E.W.: writing original draft, methodology, formal analysis, data collection and processing; K.W.: supervision, resources, project administration, review, and editing; S.T.: supervision, resources, project administration, N.S.: review and editing, project administration, validation; S.P.: review and editing, project administration, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research has received funding support The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi (KMUTT), and the Center of Excellence on Energy Technology and Environment (CEE).

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