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Biogas Production Optimization from Palm Oil Mill Effluent: Experiments with Anaerobic Reactor

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Abstract: The research domain of this work is the implementation of waste-to-energy [WtE] strategy for achieving sustainability in renewable energy supply and environment. This paper aims to present a research conducted on biogas production performance of anaerobic digestion process of palm oil mill effluent (POME). This research attempts to address the problem relating to poor biogas production performance of anaerobic digester experienced by industries with POME. Various published papers have suggested that the performance of the currently available continuous stirred-tank reactor (CSTR) based anaerobic reactor is significantly poor and not technically and financially feasible to use. A two-stage CSTR has been used with carbon-to-nitrogen (C/N) enriched inoculum at different pH for the POME digestion. The anaerobic reactor was operated at temperature 35 °C with various range of inputs. The Design Expert software is used to determine the range and levels of inputs and to determine the number of experimental runs with different combinations of inputs factors. The findings of this research demonstrate that the optimum biogas production was achieved at significant (p-value<0.05) level of organic materials utilization (R^2=62.26%) in digestion process at organic loading rate (OLR) of 5 g.VSS/L.d, C/N of 30.5, and pH of 6.6. This study concludes that the biogas production performance of CSTR could be improved by using optimum level of C/N and OLR based POME substrate. The findings of this research would be useful in palm oil mills for optimizing biogas production from POME as WtE. The novelty of this research is the use of C/N enriched inoculum (11<C/N<40) prepared from banana peel in the POME substrate for producing biogas.

Keywords: Waste-to-energy, anaerobic digestion, palm oil mill effluent, biogas production, greenhouse gas, environmental sustainability

1. Introduction

This paper aims to present a research conducted on improving biogas production performance from POME by using a two-stage standard CSTR based anaerobic reactor. The CSTR was operated with C/N enriched inoculum with high C/N (11<C/N<40), OLR (3<OLR<6), and pH (5<pH<8). Indeed, over 90% of palm oil mills have been using traditional waste stabilization pond (WSP) instead of anaerobic digester. Various published papers have suggested that the performance of the currently available CSTR based anaerobic reactor is significantly poor and not technically and financially feasible to use [1], [2]. A few published papers have also stated that the palm oil mills are reluctant to install CSTR digestor due to its poor performance and still opt for WSP [3], [4], [5]. However, the usage of WSP system contribute to the emission of methane (CH_4) and carbon dioxide (CO_2) which are known as greenhouse gases (GHG); and WSP has also appeared as a source of global warming potentials (GWP) [6]. However, this scenario suggests that

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a gap exists in the applications of CSTR in POME digestion for which biogas production has been shown to be poor. This research is designed to address this important issue. The novelty of this research is on the use of two-stage traditional engineered CSTR based anaerobic reactor with C/N enriched inoculum to optimize biogas production performance of POME.

2. Literature Review on Palm Oil Industry

The palm oil industry in Malaysia is growing rapidly to become one of the key agroindustry of the country. The total production of crude palm oil (CPO) in Malaysia was 19,919,331 and 19,516,141 tonnes in the year 2017 and 2018 respectively [7]. The average CPO yield is about 21% of the fresh fruit bunch (FFB); and other 79% of FFB appeared as wastes. This waste is regarded as hazardous solid and effluent and responsible for the emission of CH_4 and CO_2. It has been stated that POME is a potential source of GHG emission and GWP [8].

The major independent manipulating variables of anaerobic digestion process are C/N, pH, hydraulic retention time (HRT), (sludge retention time (SRT), temperature, OLR, and velocity of POME inside reactor [4], [9], [10]. It was also reported that among these variables, pH, HRT, C/N, and OLR have a significant (p-value<0.05) contribution in breaking down the chemical oxygen demand (COD) elements to biogas production.

Several authors stated that an optimal C/N between 20 to 35 exhibited a moderate nitrogen concentration for an anaerobic digestion process. [11], [12]. A study conducted by Sidik et al. (2013) on POME digestion process with a C/N range of 25 to 30; the findings demonstrated that the highest biogas yield achieved at COD reduction efficiency of 67% [13]. Nurul Adela et al. (2014) reported that at C/N 10.08-11.44, the biogas production performance of the POME was poor [14].

A few studies concluded that COD reduction efficiency is positively associated with biogas production, and the balanced nutrition in the POME substrate is a key factor. It was also reported that C/N is a potential source to provide carbon as food and nitrogen as enzyme for microbial growth [15]-[17]. However, pH in the digestion process is also a potential factor that control digestion efficiency [18].

Esposito et al. (2012) stated that organic materials digestion (biodegradability) of effluent depends on a few potential factors including C/N, pH, OLR, and HRT, but pH plays a vital role in increasing microbial population growth in digestion process [19]. It has been reported that at pH range of 6.5 to 7.8; the growth of methanogenic bacteria is significantly higher [20]. Zhang et al. (2009) found that at pH below 6.6, the environment inside the anaerobic reactor becomes acidic, and the methanogenic activities tend to decrease [21]. A few reports on biogas production efficiency have stated that the POME digestion process performance is highly dependent on pH [8], [16], [22].

Thus, the research findings revealed that a pH between 6-7 is required to provide with sufficient sustainable environment in digestion process for the growth of anaerobic bacteria [23]. Indeed, this finding concludes that a healthy digestion environment with required pH (7), the microbial activities in the POME substrate would contribute to accelerate digestion performance, and at the same time increase to reduce COD from POME to speed up biogas production. Thus, the waste biomass of POME would be used efficiently in the WtE strategy for saving the environment from the effects of CH_4 and CO_2 emission.

2.1 Theoretical Framework

The digestion in anaerobic condition is to breakdown insoluble long-chain polymers of fats, proteins, and carbohydrates into short-chain polymers [24], [25]. Total four process are involved in anaerobic digestion process. The first step is the hydrolysis for breaking long-chain polymers to a short chain carbo-hydrate compound. The second stage is the acidogenesis which produces volatile fatty acids, alcohols, ammonia, hydrogen, and carbon dioxide. The third stage is acetogenesis where fatty acids are converted to acetate, hydrogen and carbon dioxide. The fourth stage of digestion is the methanogenesis The POME digestion has carried out to produce biogas from biomass.

The first step anaerobic process is the hydrolysis for breaking long-chain polymers to a short chain form which is presented by Eq(1) [26], [27]:

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2 \qquad (1)$$

At the second stage is the acidogenesis which produces volatile fatty acids, alcohols, ammonia, hydrogen, and carbon dioxide. The third stage is acetogenesis where fatty acids are converted to acetate, H_2, and CO_2. The biogas is produced by using the outputs of acidogenesis and acetogenesis which are presented in Eq (2), Eq (3), and Eq (4) [23], [28]-[30].

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2H + 2CO_2 \qquad (2)$$

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2COOH + 2H_2 \quad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (4)$$

At the fourth stage of digestion is the methanogenesis. At this stage, CH_4 is produced [23], [28]-[30]. The acetoclastic methanogens use acetic acid to produce biogas and carbon dioxide. The steps of production are presented by Eq (5) and Eq (6) [31], [32]:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (5)$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (6)$$

All the four stages which presented by equations (1) to Eq (6) are presented in Fig 1.

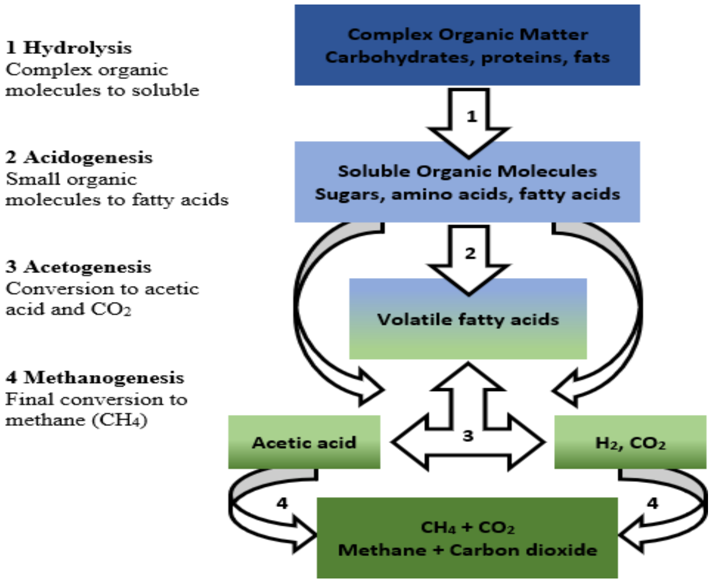

Fig. 1 - Biogas production from POME [7], [24]

2.2 Problem Statement

During CPO production, POME is generated and discharged to the environment. POME contains high level of volatile suspended solids (VSS), chemical oxygen demand (COD), and organic materials which decompose and form biogas [33]. The biogas which is emitted into the atmosphere contains about 50-75% CH_4, 25-45% CO_2, 2% hydrogen sulphide (H_2S) and some small quantity of other gases [34]. Indeed, these gases are known to be the GHG and they are responsible for GWP. The CH_4 emission of POME has a GWP of 25-times higher than CO_2 [6], [35].

However, the GHG emission from POME due to the traditional atmospheric digestion is still taking place. Though several biogas capturing plants have been installed, a significant number of plants have failed to achieve the targeted goals. It has been reported that the reasons of failure to capture biogas are mostly because of not using the required optimum value of biogas potential ingredients and digestion process control parameters in anaerobic reactors. It seems that C/N, pH, OLR, and HRT are the factors which are not optimized during anaerobic digestion and this appeared as the problem in POME digestion process. On this background, the research question is "What is the optimum value of C/N, OLR, and pH needed to optimize biogas production from POME?"

3. Research Objective

The broad objective of this study is to optimize biogas production from POME to achieve sustainable renewable energy supply and achieve environmental sustainability; and the specific objectives are:

(a) To determine the optimum value of OLR and pH to optimize biogas production.

(b) To determine the optimum value of pH and C/N to optimize biogas production.

4. Research Methodology

This section describes the methodology used to conduct experiment to achieve research goals. The research methodology has been divided into a few parts including POME sample collection, experimental setup, data collection, data analysis, and report writing. A series of experiments have been conducted by passing POME substrate through the reactor operated at 35 °C. The Design Expert (version 2018) software was used as a tool to estimate the required experimental runs to achieve accurate results [7]. This software is also known as Design of Experiment (DOE). This software was also used as a tool for data analysis to get the optimum value of inputs relating to biogas production [7].

4.1 Sample and Data Collection Analyzing Procedure

Fresh POME sample was collected from FELCRA Jaya Samarahan Sdn Bhd by using 25 L high-density polyethylene containers and transported to our laboratory. Based on the DOE outputs, a total of 20 samples were collected to conduct the required experiments.

The CSTR provides greater uniformity of system parameters, such as temperature, chemical concentration, pH, and substrate concentration. In order to improve the efficiency of anaerobic reactor and shorten the digestion cycle, two CSTR type anaerobic reactors were used to conduct the experiments. The 5 level of inputs (OLR, pH, C/N) were obtained from DOE for conducting experiment. The limits of inputs are presented in Table 1.

Table 1 - Range (limits) of inputs as independent variables

	Range and Levels				
Variables	**-α (2.3784)**	**Low (-1)**	**Central (0)**	**High (1)**	**+α (2.3784)**
X_1(OLR)	0.2431	3	5	7	9.7568
X_2(pH)	5.1729	6	6.6	7.2	8.027
X_3(C/N)	19.7971	26	30.5	35	41.2029

The estimated number of experimental runs in Table 2 were also obtained from DOE which produce the highest biogas production at a minimum resource. The DOE was also used to get response surface methodology (RSM) to determine the optimum inputs and biogas production.

Table 2 - Experimental run to achieve objective

Std	Run	Factor 1 A: OLR (g.VSS/L.d)	Factor 2 B: pH	Factor 3 C: C/N
6	1	7	6	35
4	2	7	7.2	26
5	3	3	6	35
13	4	5	6.6	19.7971
17	5	5	6.6	30.5
20	6	5	6.6	30.5
2	7	7	6	26
15	8	5	6.6	30.5
1	9	3	6	26
11	10	5	5.1729	30.5
8	11	7	7.2	35
16	12	5	6.6	30.5
3	13	3	7.2	26
19	14	5	6.6	30.5
18	15	5	6.6	30.5
9	16	0.2431	6.6	30.5
10	17	9.7568	6.6	30.5
7	18	3	7.2	35
12	19	5	8.027	30.5
14	20	5	6.6	41.2029

4.2 Research Design for Achieving Objective

This section describes the research method to achieve specific objective one. This section is designed to determine the optimum value of OLR and pH to optimize biogas production from POME. To achieve this goal, an experiment has been set-up and presented in Fig. 2. The feedstock was prepared with POME and inoculum to maintain OLR and pH limits suggested by Shahidul et al. (2018) [8]. The production of biogas was measured using water displacement method which is shown in Fig. 3. As per DOE outputs, 20 experimental runs were conducted. The experimental data were also analyzed by DOE to determine the optimum value of inputs and biogas production. The outputs of biogas production were presented in 3D graphs.

This second experiment and data analysis was related to specific objective two; which was is to determine the optimum value of pH and C/N to optimize biogas production from POME. The experiment setup to achieve this goal is the same setup as specific objective one. The feedstock was prepared with POME and inoculum to maintain pH and C/N limits suggested by Shahidul et al. (2018) [8].

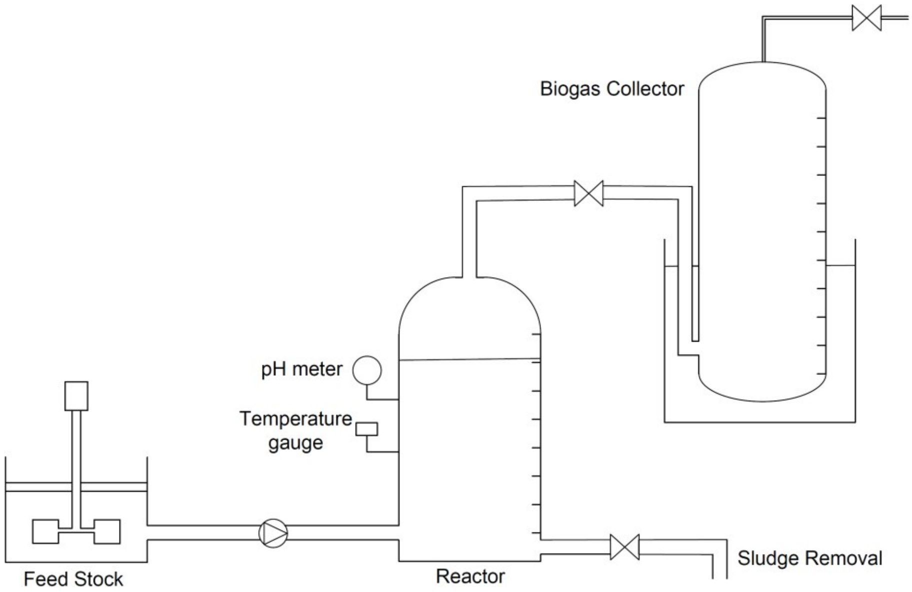

Fig. 2 - Experimental Setup

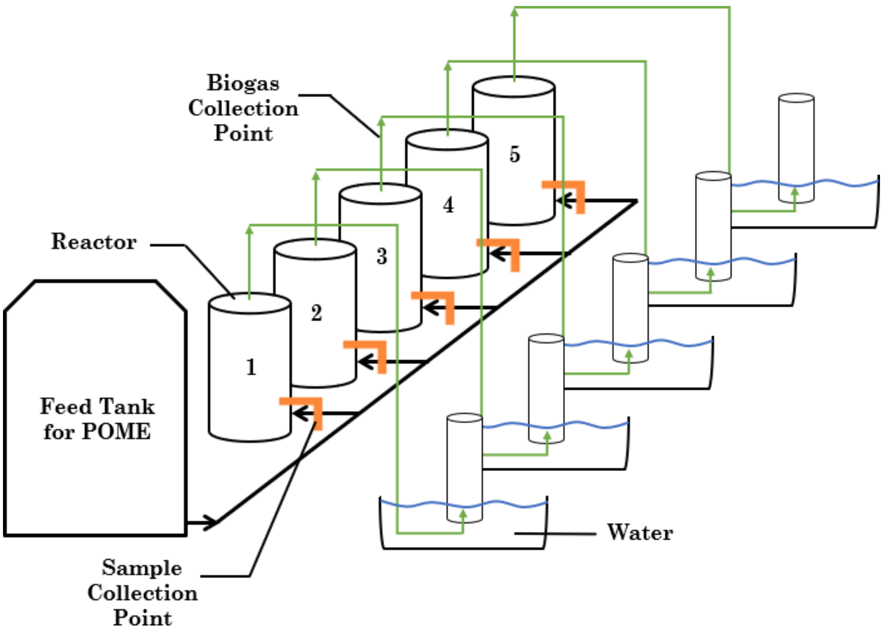

Fig. 3 - Experimental setup for biogas collection

4.3 Feedstock preparation

The substrate was a mixture of POME and inoculum. The banana peel was used to prepare the inoculum. The mesh size of the skin was converted to less than 1.0 mm and kept at an atmospheric temperature [36] before it is added into the feedstock. In order to maintain the C/N from 20 to 40, the inoculum was weighed before it was added with POME. The pH of the substrate was adjusted to 7.5 using sodium hydroxide (NaOH).Table 3 shows the characterization of the feedstock.

Table 3 - Characterization of feedstock [7]

Item	Value		
	POME	Inoculum	Substrate
COD (g/L)	96	0.0	75
pH	4.5	5.5	7.5
C/N	7	83	30

5. Results and Discussion

This section is developed for presenting research findings and to answer the research questions. This section has dived into two parts. The first part is developed to achieve specific objective one. The second part is developed to achieve specific objective two. The input control factors relating to the POME digestion process were C/N, OLR, and pH. This study was designed to identify the optimum level of C/N, OLR, and pH to optimize biogas production.

5.1 ANOVA of Research Data

The inputs and outputs data of 20 runs of POME digestion have been analyzed with DOE Software (version 2018) and the results are listed in Table 4. The mean R^2 value indicates the utilization of inputs to outputs. All inputs and output of this digestion process appear to be significant at 95% confidence level (p-value<0.05) except C/N (p-value>0.05).

Table 4 - Experimental run to achieve objective

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	6.73	20	0.3364	2.39	0.0158	Significant
A-OLR	0.8568	1	0.8568	6.09	0.0197	
B-pH	0.5910	1	0.5910	4.20	0.0495	
C-C/N	0.0209	1	0.0209	0.1486	0.7027	
Std. Dev.	0.3750		R^2	0.6226		
Mean	2.25		Adjusted R^2	0.3624		
C.V.%	16.67		Predicted R^2	-0.5964		

5.2 Determine the Optimum Value of OLR and pH to Optimize Biogas Production

The experimental data related to objective one is presented in Fig. 4. Which demonstrates that the optimum value of biogas production was 3 L/d at OLR 5 g.VSS/L.d and pH 6.6. The statistical analysis of data on digestion performance as biogas production are listed in Table 4, which shows that the digestion performance as biogas production with respect to OLR and pH was significant at 95% confidence level (p-value is 0.0197 for OLR; and 0.0495 for pH which p-value<0.05) with substrate utilization rate 62.26% (R^2 = 62.26%).

The findings listed in Table 4 and presented in Fig 4 are the answer of the research question related to specific objective number one. The graph presented by Fig. 4 indicated that required optimum input for OLR was 5 g.VSS/L.d and pH was 6.6 to achieve optimum level of biogas production. The graph also specified that at OLR greater than 5 g.VSS/L.d the biogas production has started reduced. At higher OLR means higher amount of organic materials are fed into the system which contributed to accumulate the VFA. It was stated that the high amount of VFA is negatively associated with methanogenesis process [37]. Conversely, it was also reported that the lower amount of organic materials is associated with low concentration of VFA [38]. This could result in lower production of biogas in the digestion system.

5.3 Determine the Optimum Value of pH and C/N to Optimize Biogas Production

The experimental data analysis related to objective two is presented in Fig 5. The 3D RSM graph demonstrate that the optimum value of biogas production was 3 L/d at pH 6.6 and C/N 30.5. The statistical analysis of data on digestion performance as biogas production are listed in Table 4; which indicate that the digestion performance is satisfactory as substrate utilization rate 62.262% (R^2 = 62.26%); but not significant for C/N as p-value is 0.7027; (which p-value>0.05) with. These findings answer the research question related to specific objective two. The graph presented by Fig 5. indicated that required optimum input for pH was 6.6 and C/N was 30.5 to achieve optimum level of biogas production. Indeed, the carbon in C/N is the main source of food for microorganisms to grow and nitrogen is important for the formation of enzyme [17].

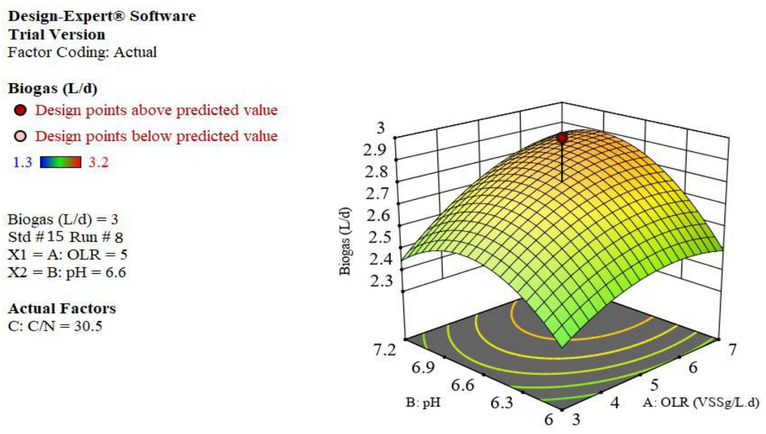

Fig. 4 - Biogas production optimization with respect to OLR and pH

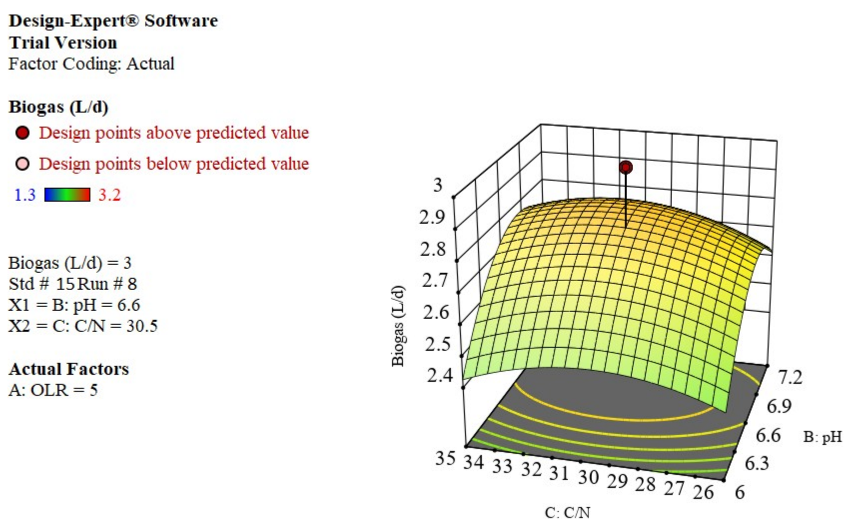

Fig. 5 - Biogas production optimization with respect to pH and C/N

It was reported that higher C/N could result in formation of carbon dioxide due to excess carbon. The substrate with higher carbon would form acid and pH in the digestion system would decrease [39], [40]. It was also reported that at lower C/N, ammonia could be produced in the substrate due to excess nitrogen; and resulting in the substrate could turn to alkaline, which is toxic [39], [40]. The methanogens activities could not function effectively in a toxic environment to produce biogas [41].

6. Scenario Analysis on Research Findings

To achieve the research goal, CSTR based anaerobic reactor was used to digest biomass and organic materials of POME. In this study, three independent variables (C/N, OLR, and pH) and one dependent variable (biogas production) were used. The research findings presented by 3D RSM graphs demonstrated that the optimum amount of biogas produced by CSTR at input for C/N 30.5, OLR 5 g.VSS/L.d, and pH 6.6. It was also found that the substrate utilization rate was 62.26% and overall performance was significant (p-value<0.05) except C/N. These findings indicate that if an anaerobic reactor could be set-up and operated with these optimum inputs, the reactor would be able to produce the optimum level of biogas production from the POME.

The methanogenic bacteria were found to be sensitive to the change in OLR. The high or low levels of OLR would contribute to reduce biogas production. The C/N was also found as a determinant of biogas yield factor. The high or low values of C/N would contribute to reduce methanogenic activities due to the formation of toxic environment in the digestion system. It was also found that methanogens were pH-sensitive microorganisms. In this aspect, Nayono (2010) reported that biogas production would increase if pH in the substrate tend to increase more than 6.5 [20]. It was found that the acetogens and methanogens performed better at near neutral environment [42]. Indeed, the combine effects of all optimum inputs were necessary to optimize biogas production.

7. Conclusions and Recommendation

The research outcomes would bring benefits to the industry, environment, and policymakers. At optimum level of biogas production and capture, less CH_4 would be emitted to the environment, resulting in a lower formation of GHGs. The continuous production of biogas from the POME would contribute to slow down climate change. Other than that, this biogas would be a reliable source of renewable energy. The benefits of capturing biogas and use as a source of alternative fuel would be helpful to reduce the reliance on fossil fuels. The usage of a standard CSTR and the addition of waste banana peel as source inoculum for increasing C/N for POME digestion would play an important role in optimizing biogas production [36].

The government of Malaysia can implement this method as waste to energy [WtE] strategy to meet energy challenge. The government and NGOs can provide incentives to new mills and existing mills which provide facilities to recover biogas. This would encourage palm oil millers to venture into green technologies which promote economic and environmental sustainability.

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