A NOVEL STUDY ON BIOGAS PRODUCTION FROM PALM OIL MILL EFFLUENT WITH TWO-STAGE ANAEROBIC DIGESTER AND NANO MEMBRANE

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ABSTRACT: *This paper describes the problem of poor treatment performance of palm mill effluent (POME); and also presents an economically and environmentally sustainable solution achieved from an experimental research. This research investigates the effects of organic loading rate (OLR), hydraulic retention time (HRT), sludge retention time (SRT), pH, and carbon to Nitrogen ratio (C/N) as the input factors with the Nano membrane that contribute to increase biogas production performance. A two-stage continuous stirred tank anaerobic reactor (CSTR) and cross flow membrane have used in series with C/N enriched inoculum for the POME digestion. The anaerobic digester and membrane were operated at temperature 35^{0}C with various range of inputs. The research findings demonstrated that OLR,HRT,SRT, and pH have played a significant (p-value<0.05) role in producing biogas with substrate utilization rate 92.50 percent (R^2=92.5), while other inputs used for digestion process were positively affected on the production of biogas and quality effluent. The findings of this research would be useful in palm oil mills for optimizing the production of biogas and recyclable water from the POME as Waste to Resource [WtR]. However, the novelty of this research is to use 'C/N enriched inoculum (11<C/N< 40) prepared from banana peel in digestion process with two stage CSTR and the cross-flow membrane for increasing POME treatment performance.*

Keywords: Palm Oil Mill Effluent, Carbon-to-nitrogen Ratio, Anaerobic Digestion, Waste Biomass, Waste to Energy [WtE], Renewable Energy, Cross Flow Membrane

RESEARCH BACKGROUND

This paper presents a research conducted on biogas and recyclable water production from POME. The fundamental theme of this research was to evaluate the effects of OLR, C/N, HRT, pH, SRT and cross flow Nano membrane on biogas and fresh water production from POME. Various reports on biogas production from POME suggested a significant percentage of palm oil mills have been using traditional waste stabilization pond (WSP) instead of anaerobic digester. The WSP is a potential source of CH_4 and CO_2 emission; and these gases are recognized as the Greenhouse Gas (GHG) and the global warming potentials [1]. It was also reported that the biogas production performance of the currently available CSRT based anaerobic reactor is significantly poor and not technically and financially feasible to use [1-3]. It has also been claimed that due to the poor performance of CSTR digester, the palm oil mills are reluctant to install this technology [1-3]; and continuing with the traditional treatment method [4]. However, this scenario suggests that a research gap exists in the processing of waste biomass of POME for which the treatment performance of this effluent is reported to be the poor. Indeed, this research has undertaken to identify the ways to reduce gap for improving biogas production performance. *However, the novelty of this research is to use C/N enriched inoculum (11<C/N<40) prepared from banana peel in digestion process with two stage CSTR and the cross-flow membrane for increasing POME treatment performance.*

LITERATURE REVIEW

This section describes the literature review published on research in POME treatment in the recent years. The aims of this review were to update the knowledge on producing biogas and water from the POME for contributing to achieve economic and environmental sustainability. The emphasis has given on the published papers described the effects of HRT, SRT, OLR, pH and C/N; and as well as membrane on biogas and water production from the POME.

The POME is a bio-effluent generate during the extraction of crude palm oil (CPO) from the fresh fruit bunch (FFB). Tis effluent contains water and a large quantity of organic materials [4], [5]. The organic materials of this bio-effluent include carbohydrates, proteins, lipid, and other micronutrients to be known as the sources of biogas [6]. The properties of biogas and water potential of the POME are listed in Table 1.

Table 1: The Biogas and Water potential of the POME [7]

Parameter	Range
Organic Material (mg/L)	15,000–100,000
Total Solids (TS-mg/L)	11,500–79,000
Volatile Suspended Solids (VSS-mg/L)	9,000–72,000
Water	92%–96%

During biodegradation process of the POME, methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphate (H_2S) are produced and emitted to the air as greenhouse gas (GHG). In order to minimize GHG emission, various types of anaerobic reactor have been used to digest organic materials aiming to produce biogas and other resources [3, [3, 8].

The C/N, pH, HRT, SRT, temperature and OLR of substrate inside the reactor have been playing a vital role in producing biogas from biomass of the POME [1, 2, 9]. It was also reported that these variables have a significant (p-value <0.05) contribution in breaking down the organic elements of biomass to form biogas and water [8].

The OLR in the digestion process is one of the determinants of biogas production performance. The higher OLR affects process stability by interrupting of the fermentation process; and also build-up volatile fatty acid (VFA) concentration, which tends to decrease pH in the POME substrate and adversely affects methanogenesis activities [10]. The lower OLR indicates the inefficient organic materials concentration in the digestion process and at this condition, the production of fatty acid reduce at the hydrolysis and acidogenesis process. The ultimate results is the decreasing of biogas production [11, 12].

The pH in the POME digestion is associated with methanogenic bacteria growth [10]. It has been reported that at pH range of 6.5 to 7.8, the methanogenic bacteria growth is found to be significantly (p-value ≤ 0.05) higher [13]. It was also reported that at pH below 6.6, the environment inside the anaerobic reactor become acidic, and the methanogenic activities tend to decrease [14]. A few studies have also reported that the biogas production is highly dependent on pH when CSTR is for anaerobic digestion [7, 15.. 16].

It has been reported that an optimal C/N between 20 to 35 exhibited a moderate nitrogen concentration in the anaerobic digestion process [7, 8]. Sidik *et al.* stated that a C/N range of 25 to 30 in the POME digestion process had appeared to be the best biogas production performance; and their research revealed that the organic materials conversion efficiency to biogas was 67 percent [17]. Nurul Adela et al. (2014) reported that the organic materials digestion efficiency to produce biogas had appeared to be poor at the C/N range of 10.08–11.44 [18]. A few studies concluded that the C/N is a potential elements for the POME digestion where carbon is used as food and nitrogen acts as an enzyme for bacteria growth [16,19, 20].

The HRT is important to maintain required contact time between substrate and bacteria for digestion of biomass. It has been reported that the range of HRT from 4 to 10 days has appeared to be adequate for the digestion of organic materials [3, 21]. Shahidul et al. (2018) found that biogas production from waste biomass of POME would be optimum within HRT from 3 to 9 days [8]. Conversely, a short HRT contribute to reduce contact time between organic materials and bacteria, and result in the insufficient reproduction of methane-forming bacteria which tend to reduce biogas yield. Indeed, the biogas production would decrease when HRT reached beyond optimum level [7].

The SRT provides matured methanogenesis bacteria in the digestion process for the utilization of the available nutrients in the POME and result in higher biogas production [7, 16]. It has also been reported that the SRT from 10 to 20 days is suitable for biomass digestion for achieving optimum level of biogas production [3, 8].

Membrane in anaerobic system has been used by a few researchers for increasing effluent quality and also to increase biogas production performance [3]. Abdurahman *et al.*, tested the methane production performance from POME by using a membrane based anaerobic digester [22]. This process comprised a cross flow ultra-filtration membrane (CUF) and an anaerobic reactor. The membrane was used to separate biomass from the effluent produced from the anaerobic digester. The digestion process was operated with a OLR ranging from 2 to 13 kg COD m^{-3}. d^{-1} SRT from 8.0 to 11.6 days and HRT from 4.6 to 5.7 days at a pH value about 7.

The research report has stated that at OLR of 13 kg COD m^{-3} d^{-1}, the process contributed to achieve 94.8 percent COD removal efficiency at HRT 6 days; and the biogas production 0.83 L $gCOD^{-1}$ d^{-1}. The study concluded that biomass separation by using UF membrane and recycled back to the process has contributed to increasing biogas production performance [8].

This literature review reveals that C/N, SRT, HRT, OLR, pH and membrane are the most potential and significant factors in the anaerobic digestion process that would contribute to increase biogas production performance from waste biomass of POME [7, 8, 23]. The literature review has also identified a research gap in biogas production from waste biomass enriched bio-effluent in the respect of optimum limit of inputs from C/N, SRT, HRT, OLR, and using of membrane.

Theoretical Framework

The biotechnology and Nano technology are the base of this research project. The biotechnology has used to convert waste biomass of POME to biogas. The nanotechnology has used to separate micro fine biomass from the effluent and recycle back to inlet of the process; and at the same time improve the effluent quality.

Biotechnology to Produce Biogas

At anaerobic condition the long-chain fats, proteins, and carbohydrates break down to the short-chain which contribute to increase biogas production from organic materials of POME [2, 20]. The various steps of biomass digestion to form biogas are depicted in Figure 1.

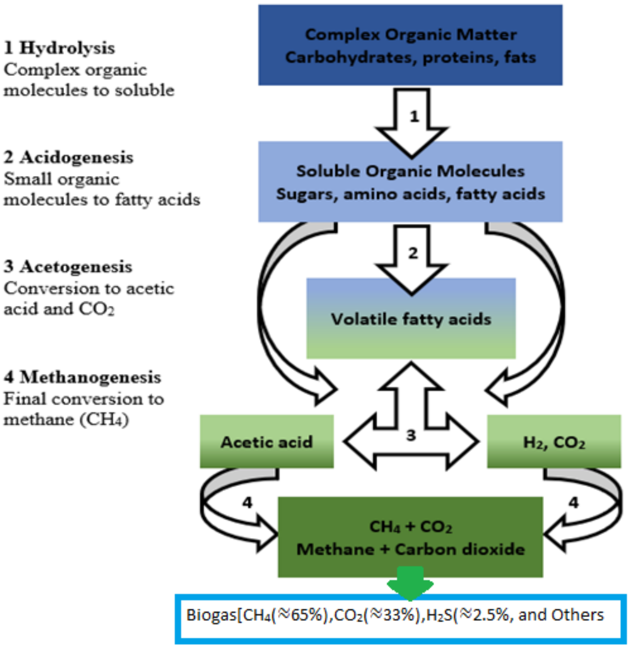


Figure 1: Biomass digestion proecess. Original work of Authors (Shahidul et al., 2018)

Nano-Technology to Reduce COD from Effluent

Effluent from anaerobic digester was fed to Nano pore membrane through port '*i*'. Estimated 96% biomass was separated from effluent in the concentration form from port 'of the membrane. From port 'f', quality effluent will be out as potable water [22].

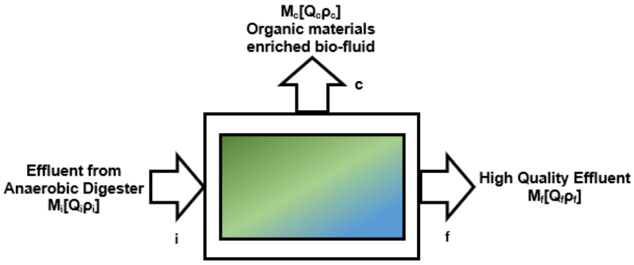


Figure 2: Nano Membrane

Mass balance:

$m_i = m_f + m_c$ $\quad [m_c \geq 96\%\, m_i]$

Fluid flow balance:

$Q_i = Q_f + Q_c$ $\quad [Q_f \geq 85\%\, Q_i]$

$COD_i = COD_f + COD_c$ $\quad [COD_f \leq 95\%\ COD_i;$

$COD_i \leq 80\%\, COD_{POME}]$

Where,
m = Mass of organic materials of POME
Q = Effluent flow

COD = Chemical oxygen demand as an indicator of biodegradable organic materials.

PROBLEM STATEMENT

The biogas production from POME is essential to reduce greenhouse gas emission. Currently, two methods have been used for POME treatment; open WSP and anaerobic reactor but none of them are commercially and environmentally feasible for biogas production to be used as energy. The CSTR anaerobic digester also being used as a means for waste biomass digestion, but its performance appeared to be insignificant [3, 11]. The reason for the poor performance is due to using of the C/N, HRT, SRT, and pH inadequately in the digestion process [7, 8]. Another identified problem is the higher COD contents in the effluent, which indicates that a significant amount of organic materials retains in the effluent in non-decompose form in the anaerobic digester. The statement of poor performance of anaerobic digester in terms of lower biogas production compare to its potentials and higher-level COD (@reduction COD≤80%) in the effluent which indicates a problem exists in the POME treatment and require to solve. With this background, a question raises "*What is the level of C/N, pH, HRT, SRT, OLR and membrane pore size needed to maintain in the anaerobic digester to achieve a sustainable biogas and effluent production performance*?"

RESEARCH OBJECTIVE

The broad objective of this research is to increase biogas production and water reclamation from the POME to contribute to achieve economic and environmental sustainability; and to achieve this goal, the work is divided into two specific objectives:

(a) To evaluate the effects of factors pH, OLR, C/N, HRT and SRT on biogas production from waste biomass of the POME.

(b) To model the cross-flow membrane performance in separating the biomass and COD from the POME.

MATERIALS AND METHOD

The research has divided into a few parts to conduct the experiment to achieve the research goals. The methodology includes the POME sample collection, experiment setup, data collection, and data analysis for report writing. A series of experiments were conducted by passing substrate through anaerobic rector and cross flow membrane operated at 35 ℃. The Design Expert (version 2018) software to be known as Design of Experiment or DOE was used as a tool to estimate the required experimental runs to achieve accurate results [7]. The DOE was also used as a tool for data analysis to get optimum value in outputs as biogas with respect to optimum value of inputs [7].

POME Sample Collection

The DOE software estimates demonstrated that a total 50 sample was essential in conducting experiments to optimize outputs. From September 2017 to February 2019, raw POME samples were collected from Bau Palm Oil Mill and Felcra Jaya Palm Oil Mill. The samples were transported to the Operations Research laboratory in Universiti Malaysia Sarawak (UNIMAS) for conducting required experiments.

Experiment Setup

To achieve research goal, two staged CSTR type anaerobic reactors have been used. The feedstock was used to mix C/N enriched inoculum and the POME. The first CSTR was used for hydrolysis and acidogenesis and it was operated at pH 5.0 in order to break down long chain organic materials into short chains [8]. Mamimin *et al.* (2015) and Kim et alhave also used this method to operate anaerobic reactor to break down long chain organic materials of POME into short chains [24, 25]. At this level, the HRT was two days and CSTR was operated at 35 ℃.

In the second CSTR, the acetogenesis and the methanogenesis processes were performed at pH from 6.5–7.5. The experiments were conducted with an inoculum prepared from waste banana peel (C/N = 83) and was added into the digestion process [26]. The C/N in the substrate was adjusted by varying the inoculum dossing rate which ranges from 11.8 to 40.3. The pH in the substrate was adjusted by adding sodium hydroxide (NaOH). However, the feed preparation with various level of inputs were estimated by using DOE software which listed in Table 2.

Table 2: The Properties of POME Substrate

Item	Value		
	POME	Inoculum	Substrate*
COD (g/L)	96	0.0	75
VSS (g/L)	30	80	35
pH**	4.5	5.5	7.5
TS (g/L)	75	11	50
C/N	7	83	30

*The properties of substrate listed is due to mixing of POME and inoculum.

**pH of substrate was adjusted to 7.5 by using of sodium hydroxide (NaOH).

The experiment setup of the research is shown in Figure 3.

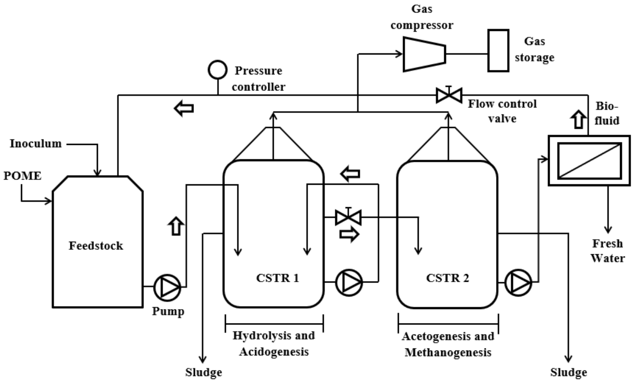


Figure 3: The experimental setup

The POME and inoculum were mixed together at feedstock to maintain required C/N and pH. The sledges were collected from both CSTR 1 and CSTR 2 and discharged to pit. The effluent was feed to membrane system to separate organic materials and water. The concentrated organic materials enriched bio fluid recycle through CSTR1 and CSTR2. The biogas was collected from both CSRT and membrane to evaluate the effects of C/N, SRT, HRT, OLR and Nano membrane on biogas production.

Research Design for Achieving Objectives

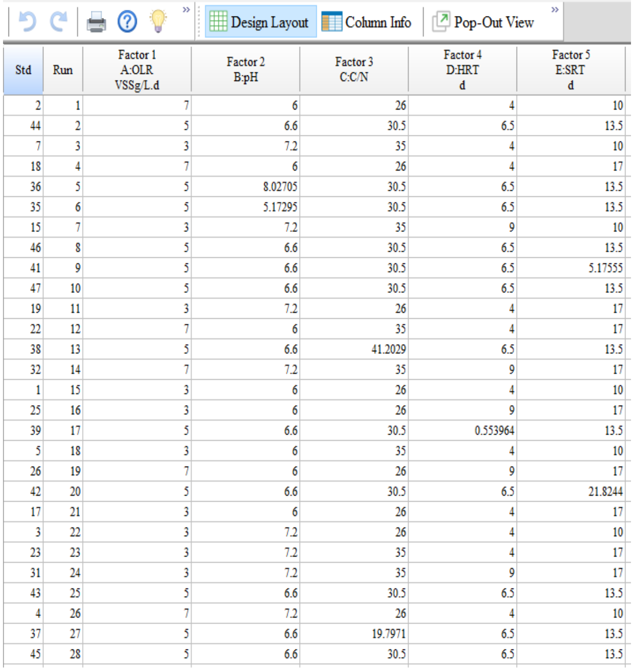
This section describes the methodology used to achieve research objectives stated in section research objective. The input values and experimental runs were obtained from DOE [7], which are listed in Table 3 and Table 4.

Table 3: Independent Variables Estimated by DOE

Variables	Range				
	-α (2.378)	Low (-1)	Central (0)	High (1)	+α (2.378)
OLR	0.2431	3	5	7	9.7568
pH	5.1729	6	6.6	7.2	8.027
C/N	19.7971	26	30.5	35	41.2029
HRT	0.5539	4	6.5	9	12.446
SRT	5.1755	10	13.5	17	21.8244

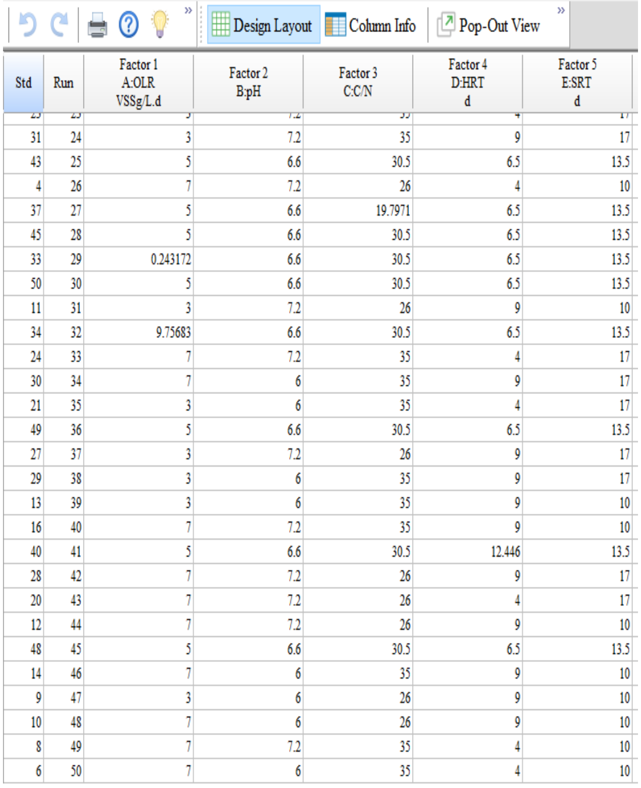
The experiments were conducted with the inputs listed in Table 3. The estimated experimental runs 50 were conducted with the combination and range of independent variables listed in Table 2 and Table 3. The detail of the experimental combinations is listed in Table 4(a) and Table 4(b).

Table 4(a): Experimental Runs for Research Objectives



Std	Run	Factor 1 A:OLR VSSg/L.d	Factor 2 B:pH	Factor 3 C:C/N	Factor 4 D:HRT d	Factor 5 E:SRT d
2	1	7	6	26	4	10
44	2	5	6.6	30.5	6.5	13.5
7	3	3	7.2	35	4	10
18	4	7	6	26	4	17
36	5	5	8.02705	30.5	6.5	13.5
35	6	5	5.17295	30.5	6.5	13.5
15	7	3	7.2	35	9	10
46	8	5	6.6	30.5	6.5	13.5
41	9	5	6.6	30.5	6.5	5.17555
47	10	5	6.6	30.5	6.5	13.5
19	11	3	7.2	26	4	17
22	12	7	6	35	4	17
38	13	5	6.6	41.2029	6.5	13.5
32	14	7	7.2	35	9	17
1	15	3	6	26	4	10
25	16	3	6	26	9	17
39	17	5	6.6	30.5	0.553964	13.5
5	18	3	6	35	4	10
26	19	7	6	26	9	17
42	20	5	6.6	30.5	6.5	21.8244
17	21	3	6	26	4	17
3	22	3	7.2	26	4	10
23	23	3	7.2	35	4	17
31	24	3	7.2	35	9	17
43	25	5	6.6	30.5	6.5	13.5
4	26	7	7.2	26	4	10
37	27	5	6.6	19.7971	6.5	13.5
45	28	5	6.6	30.5	6.5	13.5

Table 4(b): Experimental Runs for Research Objectives



Std	Run	Factor 1 A:OLR VSSg/L.d	Factor 2 B:pH	Factor 3 C:C/N	Factor 4 D:HRT d	Factor 5 E:SRT d
31	24	3	7.2	35	9	17
43	25	5	6.6	30.5	6.5	13.5
4	26	7	7.2	26	4	10
37	27	5	6.6	19.7971	6.5	13.5
45	28	5	6.6	30.5	6.5	13.5
33	29	0.243172	6.6	30.5	6.5	13.5
50	30	5	6.6	30.5	6.5	13.5
11	31	3	7.2	26	9	10
34	32	9.75683	6.6	30.5	6.5	13.5
24	33	7	7.2	35	4	17
30	34	7	6	35	9	17
21	35	3	6	35	4	17
49	36	5	6.6	30.5	6.5	13.5
27	37	3	7.2	26	9	17
29	38	3	6	35	9	17
13	39	3	6	35	9	10
16	40	7	7.2	35	9	10
40	41	5	6.6	30.5	12.446	13.5
28	42	7	7.2	26	9	17
20	43	7	7.2	26	4	17
12	44	7	7.2	26	9	10
48	45	5	6.6	30.5	6.5	13.5
14	46	7	6	35	9	10
9	47	3	6	26	9	10
10	48	7	6	26	9	10
8	49	7	7.2	35	4	10
6	50	7	6	35	4	10

The experimental data were analysed by using DOE software. The ANOVA tests were conducted for removing outlier's data, in estimating p-value and to evaluate the effectiveness (R^2) of inputs. The findings were presented by 3D and 2D graphs.

Membrane setup for waste biomass separation from effluent

Four Nano pore membranes have used for conducting this research. These membranes have also used by several researcher in solid separations process from effluent [27]–[29]. The properties of these membranes are shown in Table 5.

Table 5: Properties of Nano Membrane used

Membrane Type	Pore Diameter (nm)	NMWC (Dalton)	Hydraulic Permeability (10^{-14} m)
CODE Ll	1.26	<1000	0.899
CODE L2	1.64	1000	0.929
CODE L3	1.81	2500	0.699
CODE L4	2.47	3000	0.1.27

The hydraulic permeability of these membranes was determined from clean water flux tests before using these membranes in the experiments. The hydraulic permeability of the membranes varied with respect to its pore size. Therefore, the clean water flux was the references to determining the performance of four membranes while used in the current experiments. The experiments were carried out at 35 ℃ and transmembrane pressure drops up to 15 bar. Cross flow velocity in all experiments was 0.9 m/s [30]. Concentrations of the different effluent in both permeate and concentrate were determined by anion exchange chromatography according to the method used van Riel and Olieman [31].

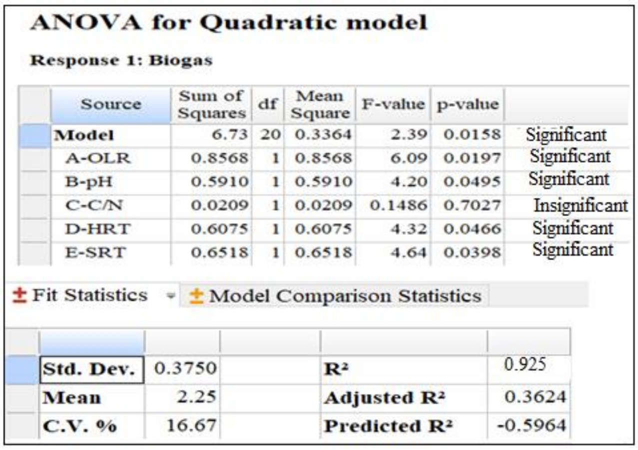
RESULTS AND DISCUSSION

This section describes the research findings and answer the research questions. The first part of this section is established for presenting the ANOVA on the data generated from the experiments. The second part is developed to state the findings of the investigations made relating to objectives of the research.

ANOVA of Research Data

The inputs and outputs of 50 runs of POME digestion have analysed with DOE Software (version 2018) and results are listed in Table 6.

Table 6: The ANOVA Outputs



ANOVA for Quadratic model

Response 1: Biogas

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	Significant
B-pH	0.5910	1	0.5910	4.20	0.0495	Significant
C-C/N	0.0209	1	0.0209	0.1486	0.7027	Insignificant
D-HRT	0.6075	1	0.6075	4.32	0.0466	Significant
E-SRT	0.6518	1	0.6518	4.64	0.0398	Significant

Std. Dev.	0.3750	R^2	0.925
Mean	2.25	Adjusted R^2	0.3624
C.V. %	16.67	Predicted R^2	-0.5964

The mean R^2 value indicates the utilization of inputs to outputs. All inputs and output of this digestion process have appeared to be the significant at 95% confidence level (p-value<0.05) except C/N (p-value>0.05).

Effects of pH on Biogas Production Performance

Biogas production with respect to pH can be seen from Figure 3; which demonstrate that highest level of biogas production has occurred at around pH 7 with a substrate utilization rate 92.5% (R^2 = 92.5%) and p-value = 0.049.

These results demonstrate that pH has a significant effect on biogas production as p-value<0.05. The outputs have presented by Figure 4.

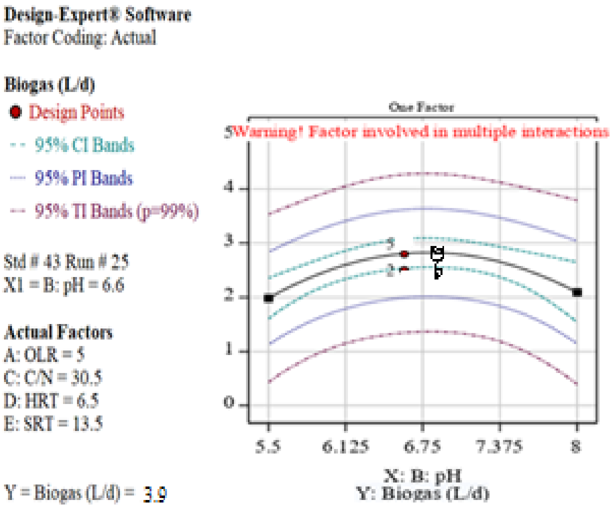


Figure 4: Effects of pH on Biogas Production

The research findings indicate that performance of methanogens activities is satisfactory at neutral (pH≈7) conditions. When pH level is below 7.0, the biogas production has appeared to be lower due to the slow growth rate of methanogenic bacteria in the digestion process. Shahidul et al. (2018) revealed that the environment in the POME digestion process becomes toxic at pH less than 6.6 and pH more than 7.3. At the toxic environment, the methanogenic microorganism strive to survive and the result is a obvious reduction of biogas production [7]. Eugene et al. (2019) and Abdelgadir et al. (2014) have conducted the similar studies and stated that pH has a positive effect on anaerobic digestion performance [16], [23].

This study revealed that pH in the POME substrate between 4.5 to 5.5 in hydrolysis and acidogenesis; and pH 6.6 to 7.2 in acetogenesis and methanogenesis would have a significant role on bacterial growth performance [15], [16]. Thus, the research findings revealed that pH has a significant (p-value<0.05) effect on biogas production. It was also found that pH from 6.9 to 7.3 is required in POME digestion process to provide a sustainable environment for the growth of anaerobic bacteria and biogas production

Effects of OLR on Biogas Production Performance

The experimental data have pelted in Figure 5, which demonstrated that the biogas production increased with OLR, and the growth trend continued until OLR reached at 5.0 g.L^{-3}.d^{-1}. Table 6 indicate that the substrate utilization to produce biogas was 92.5 percent (R^2 = 92.5%) with p-value 0.0197. These results demonstrate that OLR has a significant effect on biogas production as p-value<0.05.

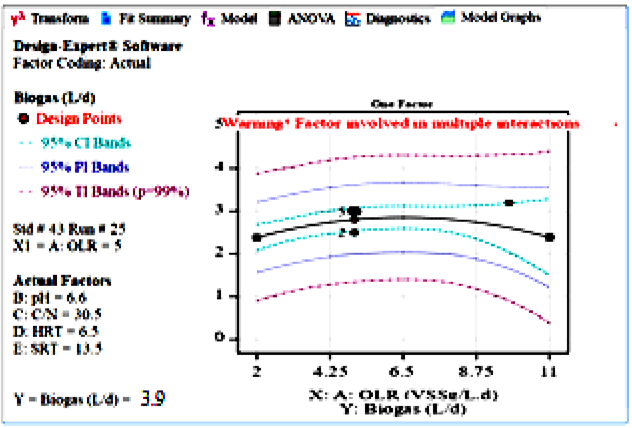


Figure 5: Effects of OLR on Biogas Production.

Figure 5 also demonstrated that at OLR loading rate beyond 5.0 g.m^{-3}. d^{-1}, the biogas production reduces. Mao et al. (2014) reported that at higher OLR, the fermentation process severally interrupted at the early stages of digestion, which affect biogas production [10]. It was also reported that at higher OLR, the pH in the digestion reduced, which contributed to decrease methanogen activities due to toxic effects and result in the reduction of biogas production performance.

Conversely, at a lower OLR, the concentration of the organic materials reduced in the digestion process and the microorganisms suffer for the lack of organic materials. At this inadequate supply of organic materials, the hydrolysis and acidogenesis processes performance tend to reduce which contributes to decrease volatile fatty acid (VFA) production , and as well as biogas production [11]. Thus, this study revealed that OLR is positively associated with biogas production; and has a significant effect (p-value<0.05) on biogas yield.

Effects of C/N on Biogas Production Performance

Experimental data were analysed to evaluate the effect of C/N on biogas production. The findings are pictured in Figure 6; which demonstrates that the biogas production has mostly occurred within pH 6 to 7; and C/N from 28 to 32. Table 6 specifies that the digestion has occurred with substrate utilization rate 92.5 percent (R^2 = 92.5 %) with p-value 0.702. These results demonstrate that C/N is positively associated with biogas production from the POME, but its effects are insignificant as p-value >0.05.

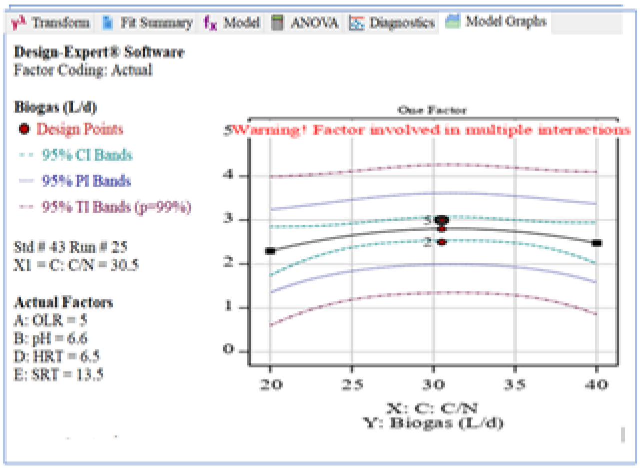


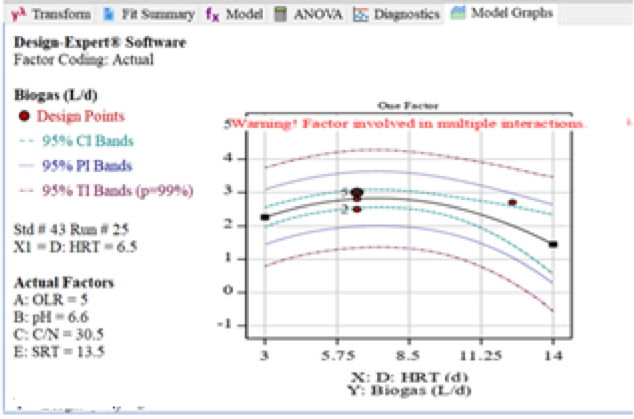
Figure 6: Effects of C/N on Biogas Production.

Figure 6 demonstrate that biogas production is in the growth curve within C/N 26 to C/N 32. It indicates that the carbon to nitrogen ratio in the substrate was adequate to maintain required environment for bacteria growth and biogas production. In this aspect, Nurliyana et al. (2015) and Iskandar et al. (2018) found that the C/N ratio in the POME substrate from 26 to 32 has played a positive role for microbial activities and biogas production [9], [20]. A lower level of C/N in the substrate indicates a higher value of nitrogen with respect to carbon. In this situation, the excessive nitrogen would turn to ammonia; and resulting in increasing the pH in the POME substrate [8]. On the other hand, lower carbon content compare to optimum value indicates less food for microorganisms, resulting in the starvation of anaerobic microorganisms, and eventually the death of bacteria. As the microbial population in the anaerobic process decreased, the biogas production performance would tend to reduce as well [16], [17]. The findings indicate that C/N has a positive effect on biogas production. A few studies have also demonstrated that the effect of C/N on anaerobic digestion is significant and has an active role to grow biogas production [23]. Thus, the research findings conclude that a C/N between 26 and 32 is required to provide with optimum level carbon and nitrogen for the growth of anaerobic bacteria.

Effects of HRT on Biogas Production Performance

Experimental data were analyzed to evaluate the effect of HRT on biogas production. The findings are pictured in Figure 7. Table 6 indicate that the substrate utilization to produce biogas was 92.5 percent ($R^2 = 92.5\%$) with p-value 0.0466. These results demonstrate that HRT has a significant effect on biogas production at a p-value<0.05.

Figure 7 indicates that the biogas production increased with HRT and continued until HRT reached 6.5 days. It could also be read from Figure 7 that the biogas production started to reduce beyond HRT at 6.5 days. In this aspect, Shahidul et al. (2018) has stated that at higher HRT, the contact time between microbial communities and organic substance increased which contributed to the rise of digestion performance of substrate and result in increasing biogas production [32], [33].



Design-Expert® Software
Factor Coding: Actual

Std # 43 Run # 25
X1 = D: HRT = 6.5

Actual Factors
A: OLR = 5
B: pH = 6.6
C: C/N = 30.5
E: SRT = 13.5

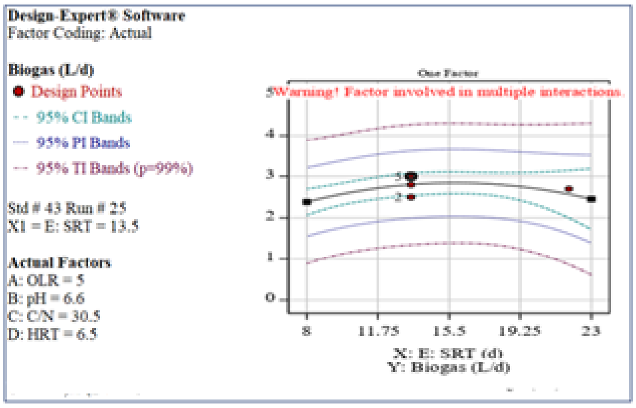
Figure 7: Effects of HRT on Biogas Production

On the contrary, when the HRT is lower than the optimum value, the contact time between microbial communities and the organic substance reduce. At this environment, the microbial activities reduces, and resulting in poor biogas production performance [10], [34]. Thus, this study concludes that HRT has a positive and significant (p-value<0.05) effect on biogas production

Effects of SRT on Biogas Production Performance

The data analysis of the experiments have plotted in Figure 8 which demonstrates that the biogas production increased with SRT and continued until SRT reached at 13.5 days. It has also been revealed that the biogas production started to reduce beyond SRT 13.5 days. Table 6 also indicates that the substrate utilization to produce biogas was 92.5 percent ($R^2 = 92.5\%$) with p-value 0.039. These results demonstrate that SRT has a significant effect on biogas production at a p-value<0.05.

A few studies reported that at adequate SRT (within 15 days) the methanogenic bacteria gets a sustainable environment in the anaerobic system and enables to grow at a faster rate [7], [23]. If SRT increases further to an extreme level (>15 days), the microorganisms available in the digestion process will begin to compete for nutrients with other bacteria, and resulting in prevention of methanogenic bacteria growth. As a result, the digestion process would be affected severely [8].



Design-Expert® Software
Factor Coding: Actual

Std # 43 Run # 25
X1 = E: SRT = 13.5

Actual Factors
A: OLR = 5
B: pH = 6.6
C: C/N = 30.5
D: HRT = 6.5

Figure 8: Effects of SRT on Biogas Production

Conversely, at lower SRT, the microorganisms would not have sufficient time for incubation to reproduce and restore the microbial population that died in the substrate [16]. When the growth rate of microorganisms is lower than the rate of microbial loss, a disaster would be occured. At this situation, the number of microorganisms in the digestion system would reduce; and result in to the reduction of biogas production [7], [23]. Thus, this study concludes that SRT has a positive and significant (p-value<0.05) effect on biogas production to a certain limit of time, and after that biomass utilization rate would to the biogas production.

The effects on Nano membrane on Biogas Production

The Membrane outputs data were analysed and listed in Table 7. The results demonstrated that membrane functions are positively associated with the increasing of biogas production and effluent quality as well. The substrates utilization rate has increase from 62.26% to 93% which is about 30% with a p-value <0.05. The biogas production has also increase about 30% with COD reduction about 19% with respect to POME treatment without membrane

Table 7: Effects of Nano membrane on Biogas Production and Effluent Quality

Estimated Parameters	Outputs with CSTR and without membrane	Outputs with CSTR and with membrane					
		L1	L2	L3	L4	Average	P-Value
Utilization of Substrate, R^2 (%)	62.26	89	91.3	93.4	96.3	92.5	0.0345
Biogas production ($L.d^{-1}$)	3	3.3	3.6	4.2	4.5	3.9	0.045
COD Reduction (%)	80	89.5	94.5	97.5	98.5	95	0.033
Effluent quality ($mg.L^{-1}$)	20,000	10,500	5,500	2,500	1,500	5,000	0.001

The overall effluent quality has improved about 75% with respect to POME treatment without membrane. The research findings conclude that Nano membrane has positive and significant (p-value <0.05) effect on biogas production from POME and effluent quality as well.

SCENARIO ANALYSIS AND CONCLUSION

To achieve the research goal, a two-staged CSTR based anaerobic reactor and NM have used to digest organic material of the POME. The research findings demonstrated that digestion mostly occurred at the C/N from 20 to 32, pH from 6.5 to 7.1, OLR from 3.0 $g.L^{-1}.d^{-1}$ to 5 $g.L^{-1}.d^{-1}$, HRT from 5 days to 6.5 days and SRT from 10 day to 15.5 days. The NM was operated up to m15 bar pressure. It was also found that these variables have positive effects on biogas production to a certain limit, and beyond the optimum limit, biogas production tend to reduce

Mao et al.(2015) stated that the excess OLR (OLR>5) in the POME digestion process affects process stability, resulting in rapid build-up of VFA concentration and decrease both pH and methanogenesis performance [10]. Conversely, at lower OLR (OLR<5) causes poor digestion performance due to short supply of organic matter. At lower OLR, the VFA production also reduce.

It was found that pH from 6.1 to 7.0, the biogas production increased due to a favourable environment for methanogens bacteria [23]. For pH<7.1, the growth rate of methanogens bacteria reduce [7] due to Alkaline environment, and resulting in the reduction of biogas production rate. But, at lower pH<6.1, the digestion process become acidic and methanogenesis activities turn to decline. Thus, this study concludes that either alkaline or acidic environment is not favour condition for optimum biogas production from the biomass of POME [29].

This experiment revealed that that at C/N>30.5, the substrate produce carbon dioxide by using excess carbon, and subsequently the carbonic acid produce in the reactor [36]. At this acidic environment, the bacteria struggle to survive and biogas production tend to decrease [36]. Conversely, at a lower C/N (<30.5) reflects high value of nitrogen which contribute to produce ammonia gas. The property of the ammonia gas is alkaline thereby contributes to increasing the pH inside reactor. In this acidic environment, microbial growth reduce and result in to the reduction of the biogas production [36].

It was also found that at longer HRT(≈6.5 days) the contact time between substrate and microorganisms increase and enhances the performance of methane-forming bacteria [8]. In this situation, the microbial population get adapt with the environment and grow faster [7] to produce more biogas [7, 8]. On the other hand, a shorter HRT (<6.5) led to the accumulation of VFA, which ends up in system failure with reduction in both microbial population growth rate and biogas production [10, 18, 37].

The SRT is found to be a contributing agent for affecting biogas production from POME. The longer SRT (>13.5 days) create favourable environment for methanogenesis to grow faster, which increase biogas production [23]. Conversely, a lower SRT(<13.5) did not get sufficient time for microbes to reproduce and restore their population [16]. When growth rate of microbes was lower than the rate of microbial loss, a washout occurred, and the methanogenic bacteria reduce to a minimum level. In this condition, the hydrolysis and acidogenesis activities take longer time to break down biomass to produce biogas.

The method used to determine efficient pore sizes from experiments is very useful. One simple experiment provides enough information to determine accurate pore size of a particular membrane which contributed to achieve 92.5% substrate utilization. Care should be taken in applying this method to very dense membranes during selection for permeated rate. Special care shall be taken for pressure when rejection rate chooses over 90%.

Separation of organic materials from a dilute mixture like POME, the Nano membrane with appropriate pore size would a practice for increasing effluent quality. However, for characterizing membrane class for low NMWC effluent, the pore size selection is important.

Based on the research findings, this study concludes that the C/N, OLR, HRT, SRT, and pH have positive effects on digestion process of POME substrate, and these inputs need to be optimized to maximize the biogas production [38, 39]. The NFM with pore size 2.47 nm has contributed to utilize 92.5% substrate which increased 30% overall performance of the system. Thus, this study is answering the research question and achieve the research objective.

These findings would be a useful reference for engineers and researchers working with palm oil mills to provide quality service in achieving higher efficiency in biogas production and quality effluent from the POME in line with the waste to resource [WtR] model for contributing to achieve economic and environmental sustainability.

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