Process Optimization of Biogas Production from Palm Oil Mill Effluent: A Case Study of a Crude Palm Oil Factory in Muaro Jambi, Indonesia

by Nazaruddin Sinaga

Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Process Optimization of Biogas Production from Palm Oil Mill Effluent: A Case Study of a Crude Palm Oil Factory in Muaro Jambi, Indonesia

Open Access

Nazaruddin Sinaga[1,*], Syukran Bestari Nasution[1], Maizirwan Mel[2,♣]

ARTICLE INFO

ABSTRACT

Article history:
Received 6 June 2018
Received in revised form 23 August 2018
Accepted 9 September 2018
Available online 11 September 2018

Keywords:
POME, biogas, biomethane, stoichiometry, optimization, digester, scrubber

1. Introduction

Indonesia's energy supply derived from fossil fuels as primary energy is not proportional to the increase in energy demand. The production and consumption of fossil energy can be seen in Figure

* *Corresponding author.*
E-mail address: nazarsinaga@undip.ac.id (Nazaruddin Sinaga)
♣ *Corresponding author.*
E-mail address: maizirwan@gmail.com (Maizirwan Mel)

1 below. Non-renewable fossil fuel sources result in continued depletion of the fuel supply in the future. Indonesia Clean Energy Development (ICED) reports that there are approximately 686 palm oil factories licensed by the Ministry of Agriculture [2]. The palm oil factory in Indonesia is the world's largest producer of palm oil with a total production of more than 40 million tons [3]. Figure 2 shows the statistics of oil palm plantations in Indonesia from 2008 to 2016. These statistics show that oil palm plantations in Indonesia are increasing year-by-year [4]. The waste generated from the CPO plant is certainly very much and can be used commercially, in addition to having a positive impact on the environment.

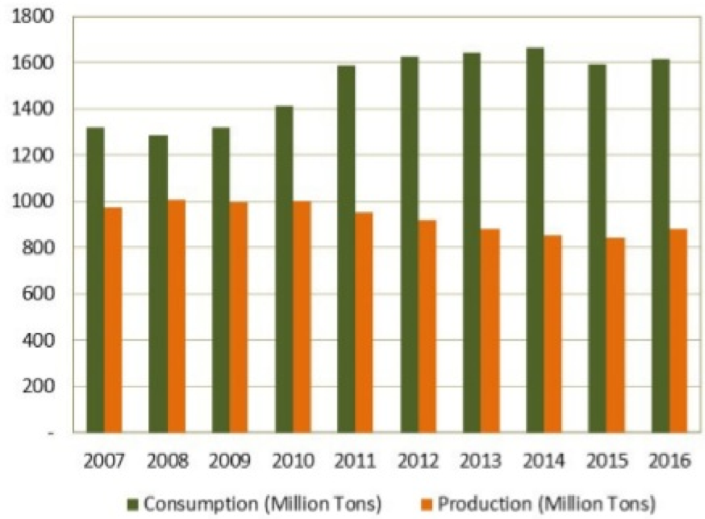


Fig. 1. Production and consumption of oil in Indonesia [1]

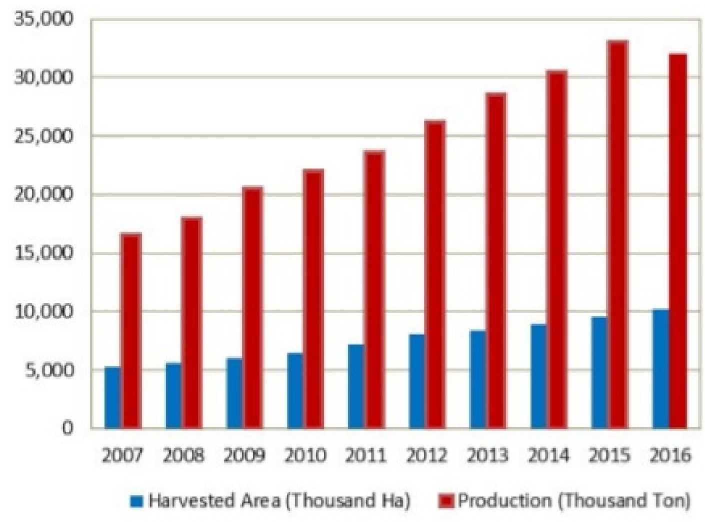


Fig. 2. Statistic of oil palm in Indonesia [4]

1.1 Palm Oil Mill Effluent (POME)

The processing of oil palm (*Elaeis gunineensis*) into Crude Palm Oil (CPO) can generate very large quantities of liquid waste or POME (Palm Oil Mill Effluent). One treatment applied to POME can be anaerobic digestion. Figure 3 shows a diagram of the palm oil processing process commonly used in palm oil mills.

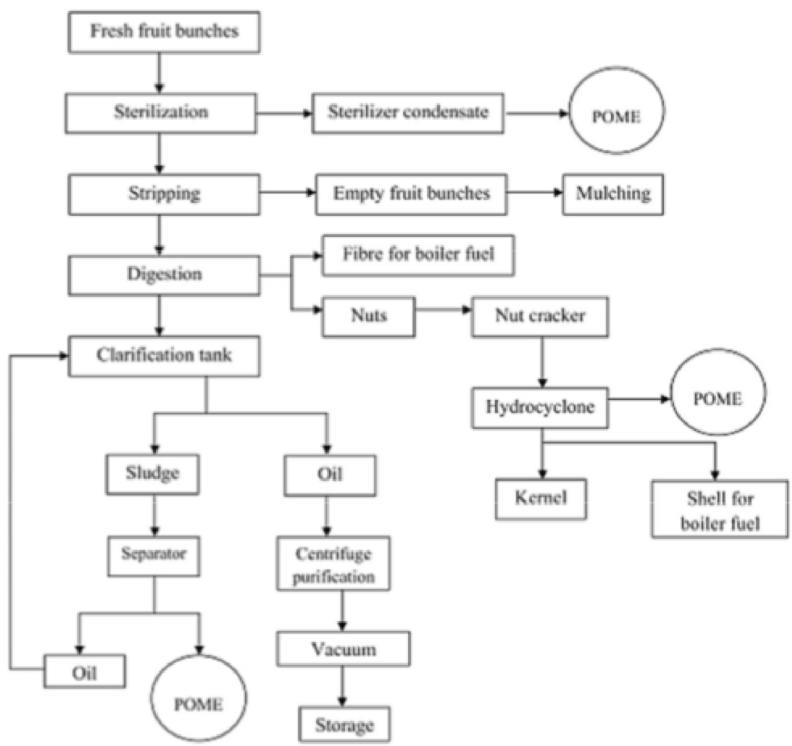


Fig. 3. Palm oil mill process [5]

During the first process, the fresh fruit bunches is sterilized in steam sterilizer for about 50 minutes at 0.3 MPa and temperature of 140°C in order to stop the rapid formation of free fatty acids during the pulping process [5]. The condensate coming out of the sterilizer becomes one of POME's main sources. The purpose of the clarification process is to separate the oil from dirt. The bottom phase of the clarifier is dried as mud or POME for further purification prior to removal [6]. Hydrocyclone is commonly used to separate the kernel from the empty shell after the breaking of the palm fruit [7]. The output of this process becomes the final source of POME. The new POME derived from refined is a brown liquid with a temperature of 80-90°C, acidic condition (pH 3.8 - 4.5), and the concentration of organic particles is quite high, COD and BOD are also high [8], as shown in Table 1. POME contains carbohydrates, protein, and fat in large quantities, with the composition of 29.55%, 12.75%, and 10.21%, respectively. The main composition of this POME is represented in Table 2.

Table 1
POME characteristics [8]

Parameter	Unit	Range
pH	-	4 - 5
BOD	mg/L	25,000 – 65,714
COD	mg/L	44,300 – 102,696
Total solids (TS)	mg/L	40,500 – 72,058
Suspended solids (SS)	mg/L	18,000 – 46,011
Volatile solids (VS)	mg/L	34,000 – 49,300
Oil and grease	mg/L	4,000 – 9,341
NH_3.N	mg/L	35 – 103
Total nitrogen (TN)	mg/L	750 – 770

Table 2
Main composition in POME [9]

Constituents	Composition (%)
Carotene	0.019
Protein	12.750
Lipid	10.210
Ash	14.880
Carbohydrates	29.550
Nitrogen	26.390
Moisture	6.990

1.2 Anaerobic Digestion

Anaerobic digestion is a natural biological degradation of organic matter without oxygen producing biogas [10]. Four stages of reaction in anaerobic digestion are hydrolysis, acidogenesis, and acetogenesis as shown in Figure 4.

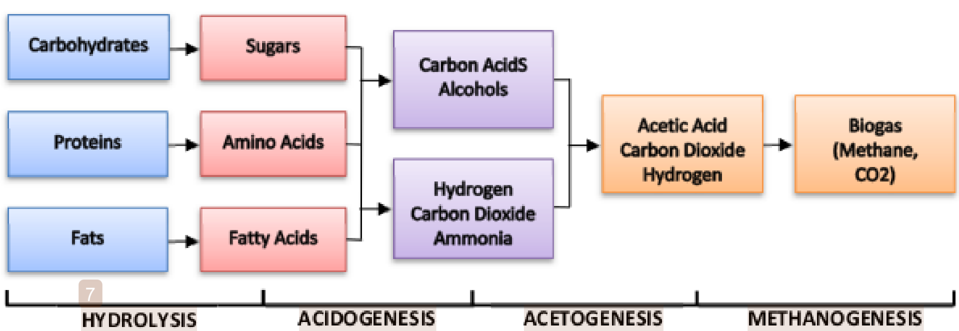


Fig. 4. Anaerobic Process of Digestion [2]

2. Methodology

2.1 Biogas Production Potential

There are two approaches that can be used to calculate the biogas production potential such as follows.

2.1.1 Chemical Oxygen Demand (COD)

Biogas produced in the system can be calculated through COD. Substrate mass rate and stoichiometric factor of 0.25 are added from chemical oxidation of methane gas (0.25 kg CH_4 is oxidized by 1 kg of O_2 [11]. The mass rate of methane can be known by equation (1) based on COD substrate.

$$W_{CH4} = 0.25 \times W_{substrat} \times COD \tag{1}$$

where,

W_{CH4} = mass flow of methane gas (kg/h)
$W_{substrat}$ = mass flow of substrate (kg/h)
COD = Chemical oxygen demand

2.1.2 Stoichiometric reaction method

The calculation of the volume and composition of biogas is calculated by using stoichiometric reactions, following the concept of the component based on the description of the process as implementation in the model of the other process steps [12]. The biogas formation of each component can be obtained by the Buswell equation and the extension of the equation in equations (2), (3), and (4).

Chemical reaction for $C_cH_hO_oN_n$ composition [13] is

$$\mathrm{CnHaObNc} + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right)\mathrm{H2O} \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)\mathrm{CH4} + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right)\mathrm{CO2} + \mathrm{cNH3} \tag{2}$$

Chemical reaction for $C_cH_hO_o$ composition [14] is

$$\mathrm{CaHbOc} + \left(a - \frac{b}{4} - \frac{c}{2}\right)\mathrm{H2O} \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right)\mathrm{CH4} + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4}\right)\mathrm{CO2} \tag{3}$$

Chemical reaction for $C_cH_hO_oN_nS_s$ composition [15] is

$$\mathrm{CcHaOoNnSs} + \left(c - \frac{h}{4} - \frac{o}{2} + \frac{3n}{4} + \frac{s}{2}\right)\mathrm{H2O} \rightarrow \left(\frac{c}{2} + \frac{h}{8} - \frac{o}{4} - \frac{3n}{8} - \frac{s}{4}\right)\mathrm{CH4} + \left(\frac{c}{2} - \frac{h}{8} + \frac{o}{4} + \frac{3n}{8} + \frac{s}{4}\right)\mathrm{CO2} + \mathrm{nNH3} + \mathrm{sH2S} \tag{4}$$

Although the calculation using COD method is possible to obtain methane gas volume, biogas composition cannot be obtained by this method. The advantage of the stoichiometric reaction method is that it can be used to calculate the volume of methane gas and biogas composition by the conversion factor fraction for different components [16].

2.2 Purification of Biogas with Pressurized Gas Scrubbing

Pressurized gas scrubbing using water as an absorber is a physical absorption process [17]. The degree of absorption of CO_2 and H_2S in the water depends on the dimensions of scrubber, gas pressure, biogas composition, water flow rate, and degree of CO_2 and H_2S solubility [18, 19]. The value of the solubility of the biogas component in water can be seen in Table 3 below.

Table 3
Solubility of biogas components in water [20]

Biogas Components	Solubility in water (mmol/kg.bar)	
	0°C	25°C
Ammonia	53,000	28,000
Hydrogen Sulphide	205	102
Carbon dioxide	75	34
Methane	2.45	1.32

2.3 Biogas Energy Content

An important part of biogas is the heat value of the CH_4 content. Other components also have energy values but have no effect in the combustion process [21]. As for the properties of CH_4 under standard circumstances (1.013 bar and 0°C):

a. Specific heat c_p = 2.165 kJ/kg.K
b. Molar mass M = 16.04 kg/kmol
c. Density ρ = 0.717 kg/m³
d. Individual gas constant R = 0.518 kJ/kg.K
e. Low heating value LHV = 50,000 kJ/kg = 36,000 kJ/m³

2.4 Process Simulation by Aspen Plus Software

Aspen Plus is a software to create and display chemical process simulations, especially to predict petrochemical processes. Aspen Plus has models where some of them are chemical process units. In addition, a list of thermodynamic properties of chemical compounds for use in the simulations is also found in Aspen Plus [22]. In this study, biogas discharge (product yield) calculations, resulting from an anaerobic POME processing, were conducted using Aspen Plus v8.6. The biogas generation process in this simulation is illustrated as in Figure 5 below. The calculation flow diagram using Aspen Plus can be seen in Figure 6 below.

Anaerobic digestion system was modelled with the concept of one-stage system and two-stages using stoichiometric method. Biogas purification method used is high pressure water scrubbing and power plant generation using gas engine. NRTL is selected as the properties method because it correlates and calculates mole fractions and activity coefficients of different compounds and to facilitate gas and liquid phases in biogas production [23]. POME can be modelled into four compounds namely water, dextrose as carbohydrate, palmitic acid/N-Hexadecanoic acid as fat, and protein soluble as protein [24]. Validation of simulation results with literature data is calculated based on the difference of biogas produced. The calculation can be calculated using the following equation (5).

$$\text{Relative difference} = \left(\frac{\text{biogas discharge from literature} - \text{calculated biogas discharge}}{\text{biogas discharge from literature}}\right) \times 100\% \quad (5)$$

The smallest difference from the calculation by equation (5) would be the composition of TSS, which is very close to the literature data and used as the optimization data.

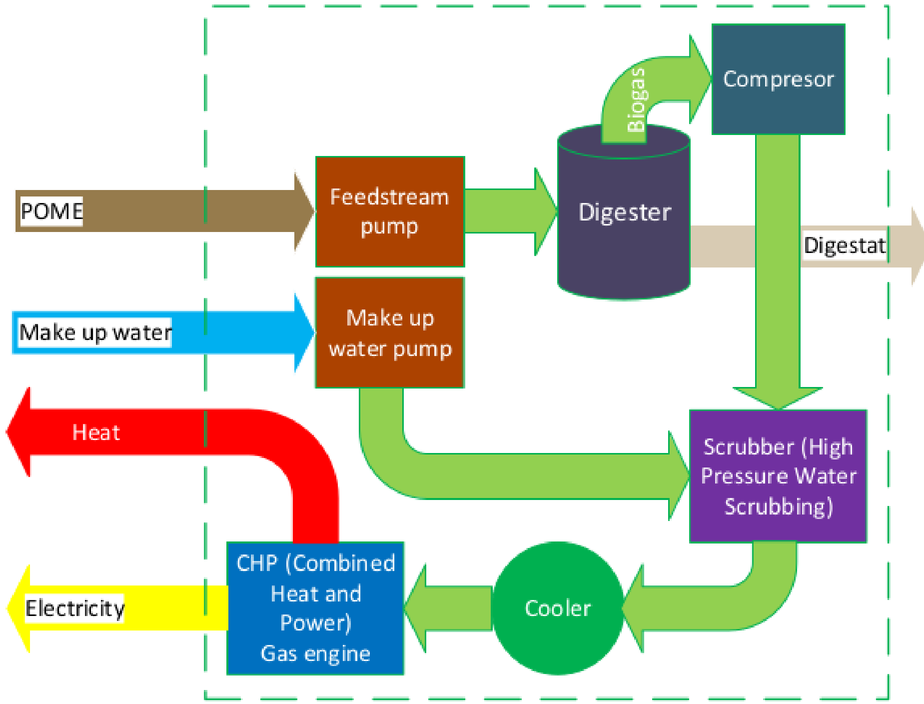


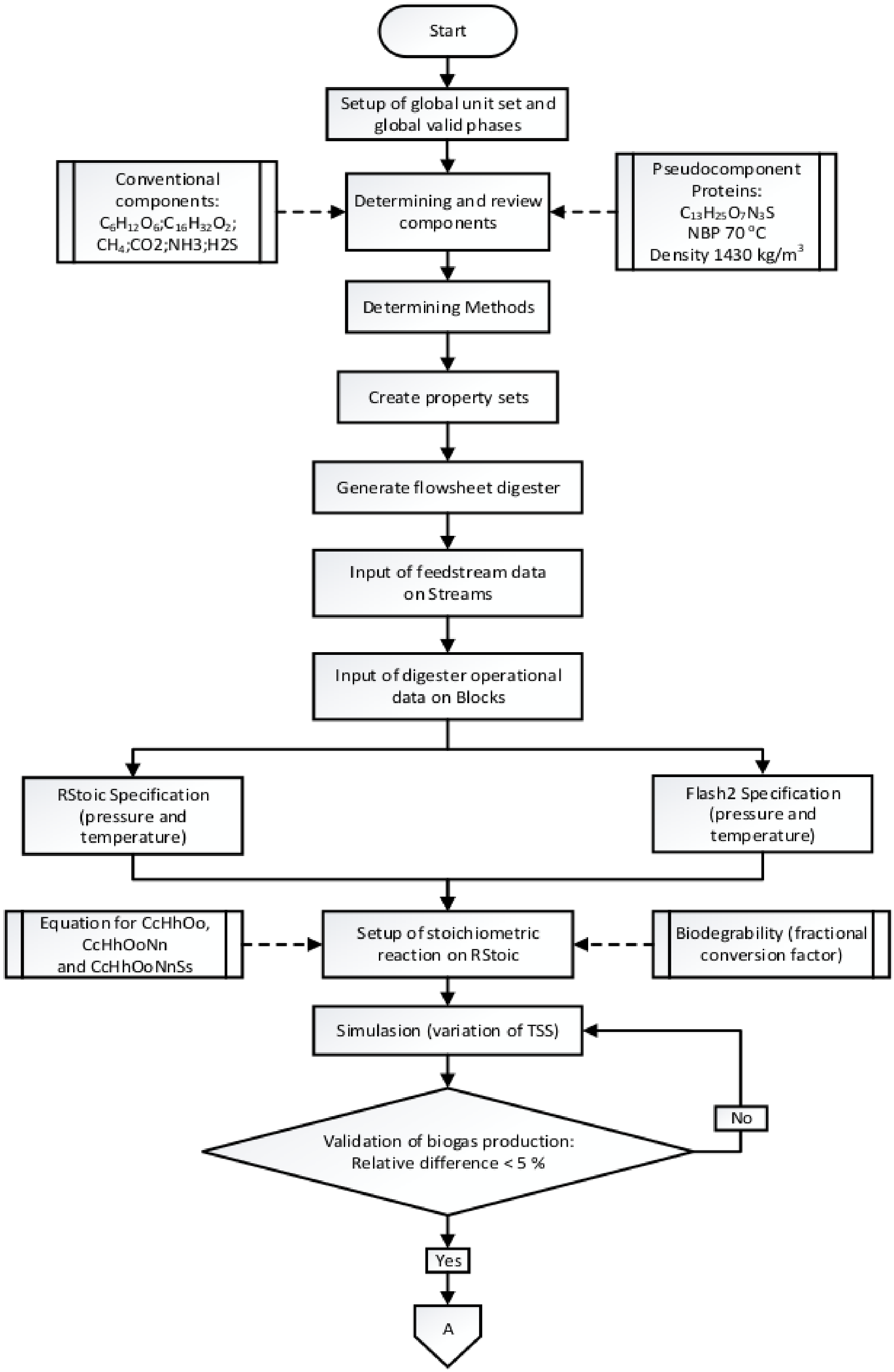
Fig. 5. Process flow in biogas power plant

3. Results

The literature data is used as a comparison of simulation results in the form of experimental or analytical data. Biogas discharge, obtained from literature data, in each case is shown in Table 4.

Table 4
Biogas data from literature

Case no.	Feed stream	Unit	COD	Biogas Production	Unit	Reference
1	205,222	m^3/y	55,000 mg/l	2,113,283	Kg/y	[25]
2	56,734,500	m^3/y	51,000 mg/l	578,093	Ton/y	[2]
3	400	m^3/d	50,000 mg/l	11,200	m^3/d	[9]
4	585	m^3/d	55,000 mg/l	603	m^3/h	[5]
5	366,854	m^3/y	55,000 mg/l	856	m^3/h	[26]


Start
Setup of global unit set and global valid phases
Conventional components: $C_6H_{12}O_6$;$C_{16}H_{32}O_2$; CH_4;CO2;NH3;H2S
Determining and review components
Pseudocomponent Proteins: $C_{13}H_{25}O_7N_3S$ NBP 70 °C Density 1430 kg/m^3
Determining Methods
Create property sets
Generate flowsheet digester
Input of feedstream data on Streams
Input of digester operational data on Blocks
RStoic Specification (pressure and temperature)
Flash2 Specification (pressure and temperature)
Equation for CcHhOo, CcHhOoNn and CcHhOoNnSs
Setup of stoichiometric reaction on RStoic
Biodegrability (fractional conversion factor)
Simulasion (variation of TSS)
Validation of biogas production: Relative difference < 5 %
No
Yes
A

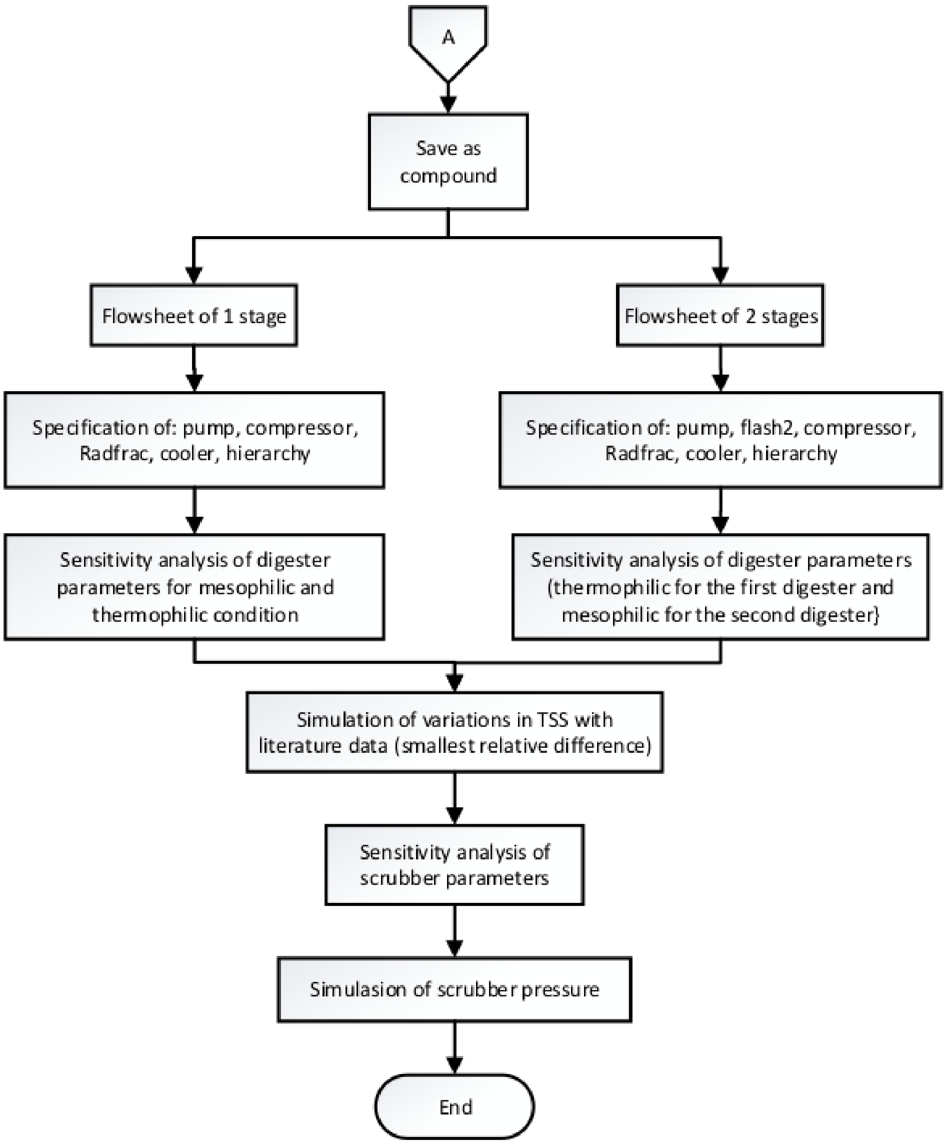


Fig. 6. Flow diagram of the simulation

3.1 Relative Difference in Biogas Production

The results and relative difference in each case as shown in Table 5.

Table 5
Relative difference in biogas production

Case no	Feed stream	Literature		Simulation				Relative Diff. (%)
		Unit	Result	Unit	Result	CH_4 (% mass)	T (°C)	
1	205,222	m^3/a	2,133,283	kg/a	2,038,950	51.10	37	4.42
2	56,734,560	m^3/a	578,093	ton/a	571,138	56.60	35	1.20
3	400	m^3/d	11,200	m^3/d	11,217	51.10	37	0.15
4	585	m^3/d	603	m^3/h	602.5	55.80	35	0.08
5	366,854	m^3/a	856.0	m^3/h	855.3	75.20	25	0.09

According to Wukovit *et al.*, [12] stoichiometric model can be used to calculate biogas potential and composition. From Table 5 above, it can be seen that the biogas discharge simulated by stoichiometric method is almost the same as the literature data, with a maximum difference of 4.42%. This model can also be used to calculate the CH_4 composition. Based on these results it can be argued that this stoichiometric model can be used quite thoroughly on to simulate the POME substrate into biogas.

3.2 Optimization of Biogas Production in Digester
3.2.1 One-stage system digester

The optimization results of CH_4 discharge on one-stage stage digester in shown in 3D graphic form below. Figure 7 is a 3D graph of digester optimization at 4% TSS composition. The 3D graph optimization of the one-stage system shows that the maximum CH_4 production is at a pressure of 1 bar and the temperature of 42°C. The maximum discharge generated is 6.002 kg/d. From the Figure 7, it is seen that with increasing pressure will decrease the biogas production rate.

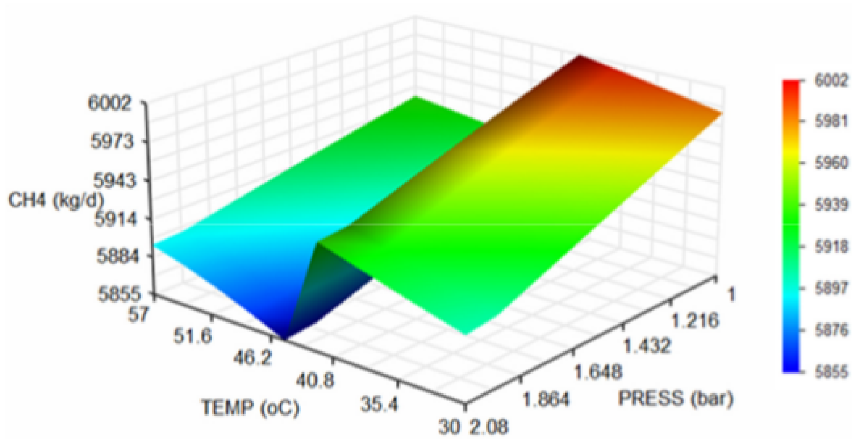


Fig. 7. Simulation result in one-stages digestion system at composition of 4% TSS

According to Vavilin *et al.,* [27], the pressure affects the solubility of a compound. If the pressure is increased then the ammonia inhibition will be smaller. Meanwhile, according to Deublein *et al.,* [20], methane gas fermentation may be inhibited by ammonia and hydrogen sulphide formations. This is what causes the production of methane gas decreases due to increased pressure as seen in the Figures 7, 8 and 9. The discharge of methane generated by mesophilic conditions is noticeably greater than that of thermophilic condition. According to Gerardi [28], this phenomenon corresponds to the fact that it is more methanogenic bacteria residing in mesophilic conditions.

3.2.2 Two-stage system digester

The results of the CH_4 discharge optimization on the two-stage digester are shown in the form of two 3D charts below. Both 3D charts show the first and second digesters in the system on the 4% TSS composition. Figure 8 is a 3D graph optimization of the first digester.

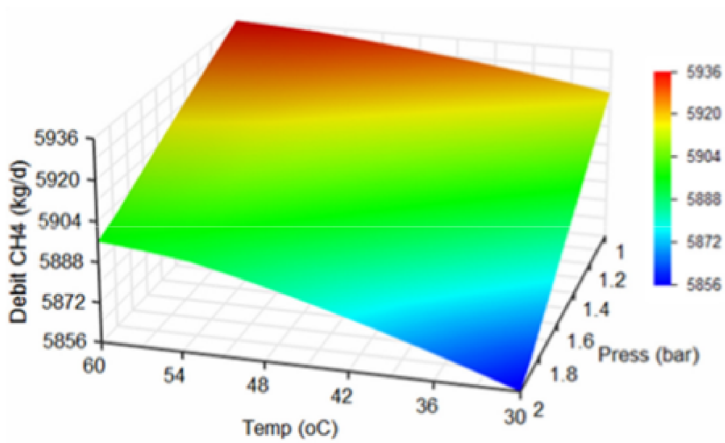


Fig. 8. Simulation result of the first digester of two-stage digestion system at composition of 4% TSS

The 3D graph optimization of the first stage two-stages system shows that the maximum CH_4 production is at pressure of 1 bar and temperature of 60°C. Maximum biogas production was at 5.935 kg/d. If the methane gas produced, it will increase the pressure in the two stages system, the methane gas production experiences the same thing as in the one-stage system also. While, the methane gas discharge in two stages system in the first digester tends to increase. This is due to the high rate of bacterial growth caused by temperature condition. According to Jay and Deublein [20], the rate of digestion in thermophilic conditions will promote the bacterial growth rapidly. For 3D graph of optimization result on other composition variation can be seen in attachment of 3D Graph of Two-stage System Optimization Result on Digester.

The maximum CH_4 production in this first digester will be used for second digester optimization in a two-stages system. The results of the optimization in the second digester can be seen in Figure 9 below. The 3D graph optimization of the two-stage system shows that the maximum CH_4 production is at pressure of one bar and temperature of 42°C. The maximum gas production generated is 1.789 kg/d. Thus, the total production of CH_4 is 7,725 kg/d. The phenomenon of a decrease in methane gas production in the second digester also occurred as previous graphs. Likewise, with the discharge of methane gas that has increased every increased in temperature. The maximum discharge of methane gas in the second digester is not as much as the first digester. This is due to the substrate entering the second digester being the sludge of the first digester having previously undergone degradation [20]. The form of 3D graph optimization of the second digester is also the same as the first digester.

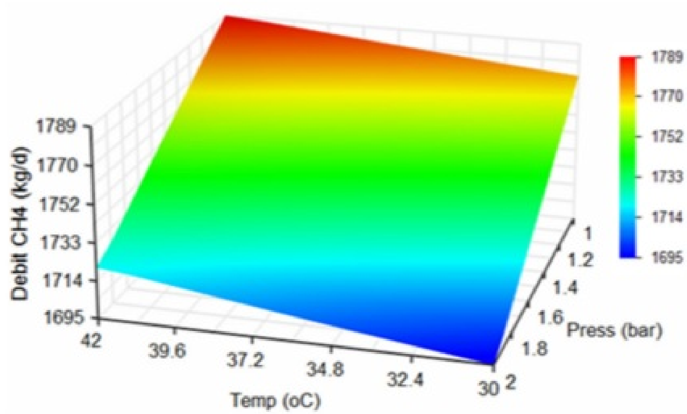


Fig. 9. Simulation result of second digester of two-stage digestion system at composition of 4% TSS

3.3 Optimization of CH_4 Production in the Scrubber

3.3.1 Biogas purification in the scrubber of one-stage digestion system

The simulated results of CH_4 production in the one-stage digestion system is shown in Figure 10, at a pressure of 9 bar. This pressure on the one-stage system becomes the optimal pressure on the biogas purification process.

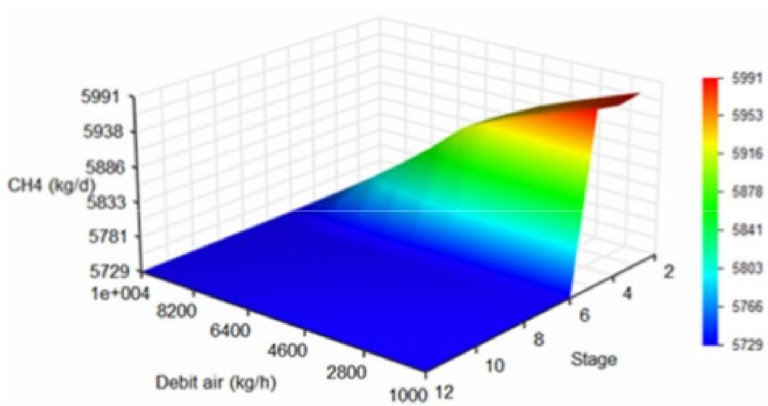


Fig. 10. Simulation result of scrubber in one-stage digestion system at pressure of 9 bar

From Figure 10, it can be seen that the maximum CH_4 production with a rate of 98.93% mass of methane gas per mass of biogas is at the water discharge of 5,000 kg/h with 5-stage purification, where the maximum yield is 5.914 kg/d. If biogas discharge is observed to the increase of purification stage, the CH_4 discharge decreases. According to Bauer *et al.,* [18] and Tippayawong *et al.,* [19], the uptake of CO_2 and H_2S in water depends on the dimensions of scrubber, water discharge, biogas composition, and pressure. Based on demonstrations by Vijay *et al.,* [29] the greater the discharge of water inserted into the scrubber the greater its absorption. This indicates that the number of stage affects the discharge of water entered. The more the stage the greater the discharge can be entered.

3.3.2 Biogas purification in the scrubber of two-stage digestion system

The result of CH_4 production optimization on two-stage digestion system is shown in 3D graphic form below. Figure 11 is a 3D graph of scrubber optimization at 10.05 bar pressure to optimise the pressure and the number of stages on biogas purification process.

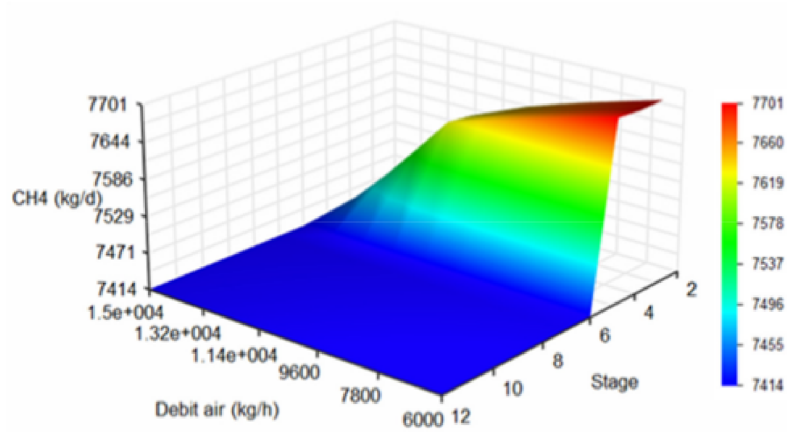


Fig. 11. Simulation result of scrubber by two-stage digestion system at pressure of 10 bar

The 3D graph optimization of scrubber in two-stage digestion system above shows that the maximum biogas production with a level of 97.24% mass of methane gas per mass of biogas is at a water flow of 11,000 kg/h and with 5-stage purification. The maximum CH_4 discharge is 7,627 kg/d. The mass water discharge on a two-stage digestion system is larger than the one-stage system. This phenomenon is caused by the amount of biogas to be purified is larger. This is in accordance with Bauer *et al.,* [18] and Tippayawong *et al.,* [19], that the absorption depends on the biogas composition. The biogas composition of the two-stage system is larger so that larger water discharges are needed as well as absorber.

4. Conclusions

From the results of simulations and optimizations performed using POME in one stage and two-stage digestion system, it can be concluded that anaerobic digestion modelling using POME with stoichiometric method has been done successfully. The composition of the POME, TSS corresponding to the literature is 3.815% and the estimation of simulated biogas produced is very close to the literature, as in the case-4 at the Muaro Jambi CPO plant. Based on this research finding, the optimum condition for 1-stage digestion is at TSS = 4%, 1 bar, and 42°C, which produces 6,002 kg/day biogas. The optimum condition of 2-stages digestion is at TSS = 4%, 1 bar, with temperature at first and second digester is 60°C and 42°C, respectively, which produces 7,725 kg/day biogas. The optimum condition in the scrubber, for 1-stage digestion, was achieved at 9 bar, water discharge of 5000 kg/hr, with 5-stage purification, which produces 5,914 kg/hour CH_4 with 98.93% methane content. The optimum condition in the scrubber, for 2-stages digestion, was achieved at 10 bar, water discharge of 11,000 kg/hr with 5-stage purification, which produces 7,627 kg/hour CH_4 with 97.24% methane content.

Acknowledgement
This research project was funded by PT Indoneka Citra Optima, Semarang Indonesia which is highly acknowledged for the financial support. Authors are grateful to the Efficiency and Energy Conservation Laboratory, Department of Mechanical Engineering for providing the lab facilities.

Process Optimization of Biogas Production from Palm Oil Mill Effluent: A Case Study of a Crude Palm Oil Factory in Muaro Jambi, Indonesia

ORIGINALITY REPORT

7%	3%	5%	4%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.researchgate.net Internet Source	1%
2	Henerica Tazvinga, Miriam Thopil, Papy B. Numbi, Temitope Adefarati. "Chapter 1 Distributed Renewable Energy Technologies", Springer Science and Business Media LLC, 2017 Publication	1%
3	Bambang Trisakti, Veronica Manalu, Irvan Taslim, Muhammad Turmuzi. "Acidogenesis of Palm Oil Mill Effluent to Produce Biogas: Effect of Hydraulic Retention Time and pH", Procedia - Social and Behavioral Sciences, 2015 Publication	1%
4	Karthik Rajendran, Harshavardhan R. Kankanala, Magnus Lundin, Mohammad J. Taherzadeh. "A novel process simulation model (PSM) for anaerobic digestion using Aspen Plus", Bioresource Technology, 2014	1%

Publication

5. B Trisakti, Mahdalena Irvan, Taslim, M Turmuzi. "Effect of temperature on methanogenesis stage of two-stage anaerobic digestion of palm oil mill effluent (POME) into biogas", IOP Conference Series: Materials Science and Engineering, 2017 — 1%
Publication

6. edrnet.com — <1%
Internet Source

7. Submitted to The University of Manchester — <1%
Student Paper

8. Ta Yeong Wu, Abdul Wahab Mohammad, Jamaliah Md. Jahim, Nurina Anuar. "Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes", Journal of Environmental Management, 2010 — <1%
Publication

9. Debalina Sengupta, Ralph W. Pike. "Chapter 25 Biomass as Feedstock", Springer Science and Business Media LLC, 2017 — <1%
Publication

10. eco-library.theplanetfixer.org — <1%
Internet Source

11. www.internationalscienceindex.org

Internet Source

<1%

12 Submitted to University of Sheffield <1%
Student Paper

13 Submitted to Dundalk Institute of Technology <1%
Student Paper

14 "Green Fuels Technology", Springer Science and Business Media LLC, 2016 <1%
Publication

15 Ashfaq Ahmad, Azizul Buang, A.H. Bhat. "Renewable and sustainable bioenergy production from microalgal co-cultivation with palm oil mill effluent (POME): A review", Renewable and Sustainable Energy Reviews, 2016 <1%
Publication

16 Submitted to Universiti Teknologi MARA <1%
Student Paper

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		

Process Optimization of Biogas Production from Palm Oil Mill Effluent: A Case Study of a Crude Palm Oil Factory in Muaro Jambi, Indonesia

GRADEMARK REPORT

FINAL GRADE

/0

GENERAL COMMENTS

Instructor

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13

PAGE 14

PAGE 15