Simulating Biogas Production Process from Palm Oil Mill Effluent for Power Generation

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Abstract. The rapid growth of the palm oil industry in Indonesia has made it the world's largest palm oil producer. However, this progress comes with a challenge as the industry generates Palm Oil Mill Effluent (POME), which poses an environmental threat if directly discharged into the environment. POME contains high concentrations of organic compounds that can be harnessed to produce energy in biogas through anaerobic treatment processes. This study aims to develop an efficient POME biogas production technique for large-scale power generation. The biogas production process with a capacity of 675.38 Kg/batch, 51,9 tonnes/year, and economic evaluation were simulated using SuperPro Designer v13.0. Biogas production from POME involves a series of stages employing anaerobic microorganisms for organic material decomposition, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The simulation results indicate that the plant can produce biogas with a composition of 86.228% methane, 1.507% water, 0.059% hydrogen, 0.016% hydrogen sulfide, and 1.959% carbon dioxide within a batch time of 114 hours. The economic feasibility simulation resulted in a Net Present Value (NPV) of $553,000, Internal Return Rate (IRR) of 19.3%, and Payback Period (PBP) of 4.22 years. Those results confirm the viability of these projects.

1 Introduction

Palm oil mill effluent (POME) stands out as the leading contributor to water pollution within the oil palm industry. In 2017, Indonesia held the top position as the world's largest palm oil producer, with a production of 35.36 million tonnes [1], followed by Malaysia and Thailand, with palm oil productions of 21 and 2 million tonnes, respectively [2]. For each

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metric ton of fresh palm fruit bunches, approximately 0.7-1 m^3 of POME waste is produced [3]. The discharged POME from the processing stages typically exhibits elevated temperatures, ranging around 70-80°C, accompanied by an acidity level (pH) of approximately 4.56 to 4.98. Furthermore, its Chemical Oxygen Demand (COD) falls within the range of 57,000 to 60,400 mg/L, while the Total Suspended Solids (TSS) measure between 0.23 to 5.44 g/L [4]. The environment faces adverse consequences from the unprocessed release of POME. Hence, there is a crucial requirement for effective POME treatment to mitigate its negative impact on the environment.

The use of POME as a raw material has attracted the attention of scientists aiming to reduce waste generated in the agricultural sector stemming from the palm oil industry. It has a beneficial influence on both the economy and the environment. POME is considered a complicated mixture comprising carbohydrates, proteins, and lipids [2]. Therefore, POME is recognized for its high biodegradable organic content, making it a favorable source for biogas generation using anaerobic treatment procedures [5]. The production of biogas from POME encompasses a sequence of steps that engage anaerobic microorganisms to break down organic matter and produce primary biogas constituents like methane (CH_4) and carbon dioxide (CO_2), alongside trace components such as hydrogen (H_2), nitrogen (N_2), and hydrogen sulfide (H_2S) [6]. This process includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis stages [2].

The utilization of biogas is a part of the renewable energy initiative, which is a governmental program aimed at enhancing energy access for communities through the use of New and Renewable Energy (EBT), particularly bioenergy. This is clearly mandated in Government Regulation No. 79 of 2014 concerning the National Energy Policy, which targets a 23% contribution from EBT to the total national energy mix by 2025. Within this 23% EBT target, bioenergy is expected to contribute around 9.7% or 23 Metric Ton Oil Equivalent (MTOE), consisting of 13.8 million KL of biofuels, 8.4 million tons of biomass, and 489.8 million cubic meters of biogas.

The electrical potential that can be harnessed from palm oil mills can reach up to 15 GW, with 1.5 GW stemming from POME. However, currently, only around 30 MW of this potential has been realized.

Variations in the biogas production procedure can influence the volume of biogas generated. Furthermore, it is imperative to conduct process optimization and economic assessments to establish the viability of a biogas production facility. Hence, the need to optimize biogas generation by employing diverse methods becomes crucial. This research aimed to assess the co- digestion potential of POME by introducing cow manure within an industrial-scale batch process. The investigation sought to identify the optimal sludge proportion to enhance the anaerobic bio-methanation process while also conducting a feasibility analysis of the biogas power generation system utilizing POME. In this research, a techno-economic assessment was conducted to analyze the treatment of POME and the production of biogas. This analysis was performed utilizing a commercial process simulation tool, specifically SuperPro Designer v13.0.

2 Material and Methods

The simulation procedure is conducted in batch mode utilizing SuperPro Designer v13.0 software. This software employs both primary and secondary data as input for the simulation. The suggested factory is situated within Karawang, West Java, which is recognized as an industrial zone. This industrial zone spans an extensive area of 13,718 hectares.

2.1 Material

POME serves as the resource for biogas generation, requiring a biodigester to facilitate the conversion process. Enhancing the anaerobic digestion process, cow manure is used for its methanogenic bacteria content [7]. The equipment used are cooler, mixer, gas compressor, absorber, degasifier, gas burner, and gas expander.

2.1 Method

The primary application of the anaerobic digestion process is for the treatment of waste sludge and high- strength organic wastes [3]. This method entails the breakdown of organic materials by microorganisms in the absence of oxygen, resulting in the production of digestate and biogas. It offers advantages such as lower biomass production and the generation of energy in the form of methane. The process can be carried out within either the mesophilic temperature range (30−35 °C) or the thermophilic temperature range (50−60 °C). The overall anaerobic degradation of waste involves four fundamental steps: (1) hydrolysis, (2) fermentation (acidogenesis), (3) acetogenesis, and (4) methanogenesis, as shown in Fig 1 [7].

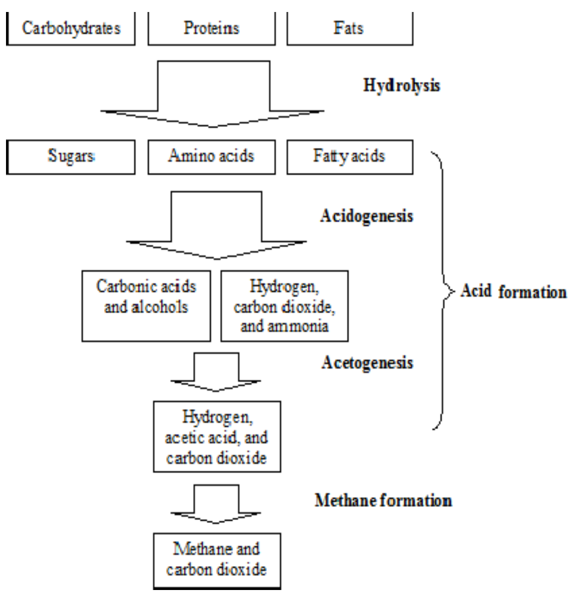

Fig. 1. Anaerobic Digestion Pathway [7]

3 Result and Discussions

3.1 Simulation Results

The overall simulation stream for biogas production is shown in Figure 2. POME is directed into the cooler with a flow rate of 15,000 kg per batch to lower its temperature to 20°C. Cow manure is introduced at a flow rate of 1,500 kg per batch to break down POME using enzymes produced by the bacteria. This mixture subsequently moves into the hydrolysis stage (AD-105) with a batch flow rate of 16,500 kilograms. During the hydrolysis stage, complex organic molecules are disassembled into simple sugars, amino acids, and fatty acids. The hydrolysis products are subsequently fed into the second stage, the acidogenesis tank (AD-101). The second stage involves the biological process of acidogenesis, which converts the hydrolysis products into short-chain organic acids, specifically C1–C5 molecules (such as butyric acid, propionic acid, acetate, acetic acid), alcohols, hydrogen, and carbon dioxide. The substances generated during the acidogenic phase act as a source of nutrients for a different group of bacteria, specifically those involved in the acetogenic phase (AD-102). During the acetogenic phase, acetogenic microorganisms consistently convert energy-releasing hydrogen (H_2) and carbon dioxide (CO_2) into acetic acid. The final stage involves the biological process of methanogenesis (AD-103). Methanogenesis is employed to transform acetic acid into methane as the ultimate product resulting from anaerobic degradation processes. The resulting digestate comprises remnants of bacteria and reaction by-products that can be utilized as fertilizer.

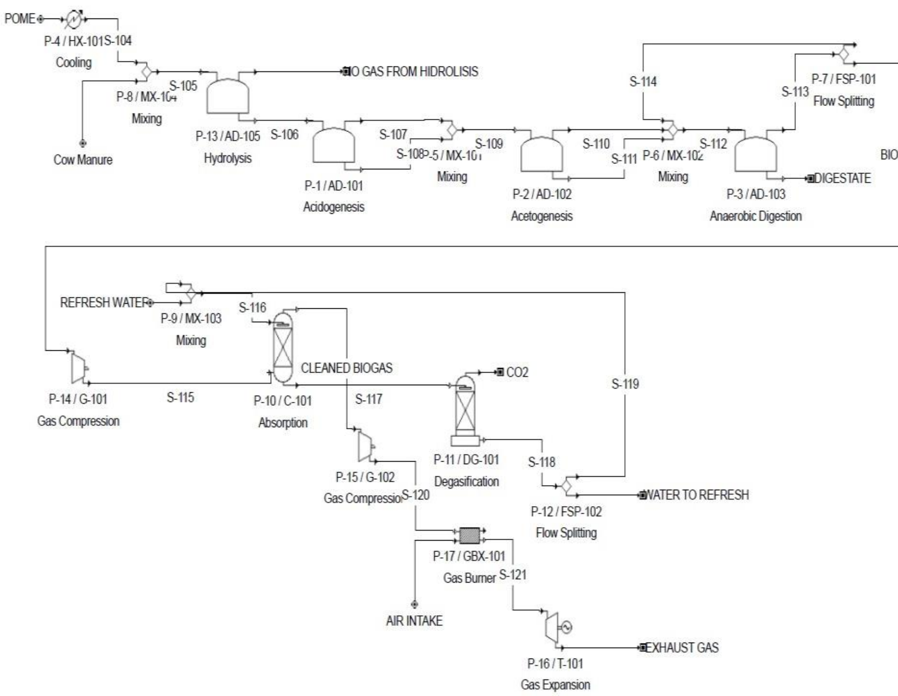

Fig. 2. Simulation flows of biogas production from POME

Table 1. Overall Mass Balance for Biogas Production

Material	Input (kg/batch)	Output (kg/batch)
POME	15,000	50.6680
Cow manure	1,500	0
Air intake	100	0
Carbon dioxide	0	15.3468
Hydrogen sulphide	0	0.1235
Hydrogen	0	0.4601
Methane	0	675.3838
Ammonia	0	1.1004
Nitrogen	0	76.7118
Water	100	11.7998
Oxygen	0	2.3288

The gaseous product generated during methanogenesis undergoes compression to reach a pressure of 5 bar (G-101). Typically, biogas is composed of methane (CH_4), carbon dioxide (CO_2), and various contaminants such as hydrogen sulfide (H_2S) and moisture. The high CO_2 concentration in biogas leads to a reduced calorific value of biomethane (CH_4) gas. Therefore, it is necessary to further purify the biogas to eliminate the CO_2. The removal of both CO_2 and H_2S from biogas through adsorption is a straightforward and effective approach. It has reported successful simultaneous and competitive removal of impurities using adsorption to enhance biogas quality and increase CH4 content [8]–[10]. Any remaining CO_2 gas is absorbed by absorbers (C-101) using clean water (at a rate of 100 kg per batch). Subsequently, a degasification process is performed to eliminate hydrogen sulfide (DG-101). Furthermore, methane gas, devoid of CO_2, is also compressed to the same pressure of 5 bar (G-102). There is a chemical reaction between methane and oxygen, resulting in the production of CO_2 and water, with an intake of 100 kg per batch of air. Finally, the gas undergoes expansion, increasing its value, and is released at an outlet pressure of 1.013 bar (T-101). The overall mass balance was calculated, as detailed in Table 1, with input data sourced from the flow entering the anaerobic digester and output data collected from the gas expander.

The simulation results indicate that the plant can produce biogas with a molar composition of 91.10% methane, 1.42% water, 0.49% hydrogen, 0.01% hydrogen sulfide, and 0.75% carbon dioxide within a batch time of 114 hours. When we compare the simulation results with data from existing literature on potential biogas production, it becomes evident that the process stages employed in the simulations yield biogas products with a molar composition of CH_4 (91%), which is greater than what is reported in the literature, namely 60 :40 for ratio of CH_4:CO_2 [11].

The overall process data is showin Table 2. Assuming a power plant conversion efficiency of 35% and a calorific value of 25 MJ/m^3 for biogas, the electricity generated is 8,095 kWh for the production of 675.3838 kg per batch of biogas.

Table 2. Overall Process Data

Aspect	Value	Unit
Annual operating time	7,914	Hour
Unit production ref. rate	220,175.11	MP/yr
Batch size	675.3838	Kg/MP
Batch time	114	Hour
Number of batches per year	326	Batch/yr

3.2 Economic Analysis

In this section, we assess the financial feasibility of producing biogas from POME treatment. The initial equipment costs were obtained from equipment suppliers and SuperPro Designer. Operating expenses encompass expenses related to raw materials, air emission treatment, and labor costs. In this particular scenario, the cost of POME is 0.59 $ per kilogram, while cow manure is 0,26 $ per 100 kilograms. The labor cost is assumed to be at 0.66 $/hr for this case. The sources of income taken into account include revenue from biogas and the sale of dried sludge as fertilizer (please refer to the unit prices in Table 2). These calculations were conducted using the economic assessment tool provided by SuperPro Designer v13.0, and the outcomes are presented in Table 3.

Table 3. Unit price for revenue streams

Revenue stream	Value	Unit
Biogas	13.7	$/kg
Fertilizer	0.04	$/kg

There are two categories of expenses to consider: the total capital investment (TCI) and the operational cost. TCI encompasses all fixed capital costs, along with the calculated working capital cost. According to the findings in the economic report, a total capital investment (TCI) figure of $634,000 was derived. A breakdown of this calculation is provided in Table 4.

Table 4. Total Capital Investment for Biogas Production

Aspect	Cost (USD)
Direct Fixed Capital	348,000
Working Capital	269,000
Start-up Cost	17,000
Total Capital Investment	**634,000**

Operating costs encompass the annual expenses necessary for the operation and include costs related to raw materials, labor, and factory facility maintenance. According to the findings in the Economic Evaluation Report (EER) for this plant, the annual operating cost is $3,027,000. A breakdown of the operational expenditure (OPEX) is presented in Table 5.

Table 5. Total Capital Investment for Biogas Production

Aspect	Cost (USD)/yr
Raw Materials	2,888,000
Labor-Dependent	46,000
Facility-Dependent	65,000
Laboratory/QC/QA	7,000
Utilities	20,000
Total	**3,027,000**

TCI and operational costs have a significant impact on economic parameters such as ROI, PBP, IRR, and NPV. The overview of the Economic Evaluation Report (EER) from this investigation is presented in Table 6.

Table 6. Economic Evaluation Report for Biogas Production

Economic Parameter	Value
Return on Investment (ROI)	23.36%
Payback Period (PBP)	4.28 years
Internal Rate of Return (IRR)	18.92%
Net Present Value (NPV)	537,000 USD

According to the data in Table 5, it is projected that the plant will achieve a return on investment of 23.36%. As the ROI in the factory decreases, the factory's profit- generating capacity diminishes accordingly. The estimated breakeven period is approximately 4.22 years, and the internal rate of return (IRR) stands at 18.92%. A desirable POME-to-energy project typically aims for an IRR within the range of 11% to 23% [3]. Therefore, based on these findings, the project under examination is considered economically viable, and the POME-to- energy initiative is anticipated to generate significant revenues while simultaneously promoting sustainability in terms of energy and environmental considerations.

4 Conclusion

The research on biogas production from POME treatment was successfully carried out using a simulation tool, specifically SuperPro Designer v13.0. This study confirmed the viability of capturing biogas through anaerobic treatment of POME. For a POME feed rate of 15,000 kg/batch, the study yielded 675.38 Kg/batch, which is equivalent to 51,9 tonnes/year of biogas produced. Based on the scheduling outcomes, a single batch cycle spans a total duration of 114 hours. The economic evaluation has demonstrated that the plant is financially feasible and sustainable. Projections indicate that the plant is expected to achieve a Net Present Value (NPV) of $537,000 and an Internal Rate of Return (IRR) of 18.92% within a payback period of 4.28 years.

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References

1. M. Yanita, D. Napitupulu, Z. Alamsyah, H. D. Ernawati, Elwamendri, G. Fauzia, IOP Conf. Ser. Earth Environ. Sci., **782,** 3 (2021)
2. M. M. A Aziz, K. A. Kassim, M. ElSergany, S. Anuar, M. E. Jorat, H. Yaacob, A. Ahsan, M. A. Imteaz, Arifuzzaman, Renew. Sustain. Energy Rev., **119,** (2019).
3. X. Lok, Y. J. Chan, D. C. Y. Foo, J. Water Process Eng., **38** (2020)
4. BPS, *Statistik Kelapa Sawit Indonesia 2021*. (2022)
5. J. D. Bala, J. Lalung, N. Ismail, Int. J. Recycl. Org. Waste Agric., **4,** 1 (2015)
6. D. Andriani, A. Rajani, Kusnadi, A. Santosa, A. Saefudin, A. Wresta, T. D. Atmaja, IOP Conf. Ser. Earth Environ. Sci., **483**, 1 (2020)
7. D. Deublein and A. Steinhauser, *Biogas from Waste and Renewable Resources*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA, (2008)
8. E. Kusrini, M. Lukita, M. Gozan, B. H. Susanto, T. W. Widodo, D. A. Nasution, S. Wu, A. rahman, Y.D. I. Siregar, Int. J. T, **4**, (2016)
9. E. Kusrini, S. Wu, B. H. Susanto, M. Lukita, M. Gozan, M. D., Hans, A. Rahman, V. Degirmenci, A. Usman, Int. J. Technol., **10**, 6 (2016)
10. A. Pertiwiningrum, M. A. Wuri, A. W. Harto, R. Budiarto, M. Gozan, Int. J. GEOMATE, **16**, 55 (2019)
11. M. Gozan, N. Aulawy, S. F. Rahman, and R. Budiarto, Int. J. Appl. Eng. Res., **13**, 8 (2018)