# A Comprehensive Review Of Utilization Of Palm Oil Mill Effluent (POME) For Sustainable Biogas Production

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## Abstract

In recent years, researchers have focused on developing alternative fuels derived from biological resources, including Palm Oil Mill Effluent (POME). These efforts aim to reduce environmental pollution and generate clean and renewable energy, contributing significantly to global sustainability goals. Biogas is a renewable, environmentally friendly, and inexpensive energy source with the potential to help achieve these goals, offering a viable pathway for decentralized energy production. Anaerobic Digestion (AD) is a crucial method for producing biogas, a process that involves the metabolism of microorganisms in the absence of oxygen. However, improvement of biogas quality is essential to meet consumption requirements, particularly for grid injection or vehicle fuel applications. The efficiency of technological improvement is evaluated based on several criteria, including operation and maintenance costs, investment costs, methane recovery, and methane losses. Membrane technology has lower operation and maintenance costs compared to chemical absorption technology. However, it requires significant investment costs. This study aims to comprehensively assess the various cutting-edge technologies and their techno-economic feasibility, considering their environmental footprint, available for biogas production, upgrading, and use. The study also offers a robust framework that matches the required biogas quality for each potential use with the required upgrading technology. In addition, this study also examines the prospects associated with biogas production, upgrading, and consumption, as well as the government regulations that can facilitate their implementation, emphasizing the need for supportive policy frameworks.

Keyword : Palm Oil Mill Effluent, Biogas, Anaerobic Digestion, Upgrading, Membrane technology

## 1. Introduction

Biogas has become the focus of attention as a clean and renewable energy source that can reduce dependence on fossil fuels and help mitigate global climate change (1). Biogas is produced from the anaerobic decomposition of organic matter, resulting in a gas consisting mainly of methane ($CH_4$) and carbon dioxide ($CO_2$), with a methane content of 50-75%, making it a strong candidate as an alternative fuel (2-4). The main advantage of biogas lies in the simplicity of its production process compared to biofuels such as ethanol and methanol, which require more complex chemical and biological processes (5). The primary process of biogas production is Anaerobic Digestion (AD), which involves four stages of microbiological reactions: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (6).

With increasing attention to clean energy, various countries have implemented policies that support the development of biogas. For instance, the European Union has set targets for biofuel use in the transportation sector, and the United States has set ambitious goals for renewable energy production (5). Globally, the growth of biogas installations continues to increase. In Germany, there were more than 3,700 agricultural biogas installations in 2007, while in China, the use of small-scale digesters has grown rapidly as a solution for waste management and energy production. A study in Guangzhou, China, estimated that food waste has a high potential to produce biomethane and fertiliser, and contribute to the reduction of greenhouse gas emissions (7-9).

Therefore, several literature reviews have emphasized the importance of a comprehensive evaluation of the entire biogas production and utilization chain to support the energy transition towards sustainability (12). One of the biogas source that catch the eyes of the world is Palm Oil Mill Effluent. The compound is a solid-liquid waste that contains various impurities, such as hydrogen sulphide ($H_2S$), carbon monoxide (CO), and other volatile

S. C. Asih et al. (eds.), *Proceedings of the 19th International Conference on Quality in Research (QiR 2025)*,
Advances in Engineering Research 303,
https://doi.org/10.2991/978-94-6239-717-0_29

compounds. The physicochemical properties of POME indicate that if discharged untreated into the environment, POME can cause pollution (13). The adverse environmental impacts associated with POME can be mitigated through treatment, while utilizing useful energy sources such as biogas, thereby increasing the value of the POME waste itself. This research objective is to examine the key parameters that are involved in biogas production from POME and how it can be contributed to maximizing the entire biogas production and utilization chain to support the energy transition towards sustainability.

## 2. Material and Methods

### *2.1 Materials*

#### *2.1.1 POME*

Palm oil is extracted from fresh fruit bunches (FFB) through dry or wet milling processes. The wet milling process is the most common in palm oil-producing countries (14, 15). POME is constantly associated with environmental burdens due to the huge discharge of wastewater during the milling process (16). Awotoye et al. (14) estimated that 5-7 tons of fresh water are required to mill one ton of FFB, of which 50-79% ends up as POME (17, 18). In large mills, POME is primarily generated from sterilisation condensate, separation (clarification) sludge, and hydrocyclones during the palm oil milling process (19-21). In small mills, POME is primarily generated from sterilisation and clarification condensates, rather than from hydrocyclones. Crude POME, consisting of complex vegetative material, is a thick, brownish, watery colloidal slurry from the crushing of palm fruit mesocarp (22,23). POME is a colloidal suspension of substances that is 95-96% water, 0.6-0.7% oil and 4-5% total solids, including 2-4% suspended solids and high concentrations of organic nitrogen (24-26). The brownish and colloidal suspension of POME contains high concentrations of organic matter, high amounts of total solids, oil and grease, chemical oxygen demand (COD) and biological oxygen demand (BOD). However, POME also contains large amounts of plant nutrients, such as nitrogen, potassium, magnesium, and calcium [27], as well as cadmium, copper, chromium, and iron [27]. The physicochemical properties of POME are presented in Table 2. Raw or partially treated POME has a very high content of degradable organic matter, which is partly due to the presence of unprocessed palm oil (28).

**Table 1.** *Physicochemical Parameters* POME

| Parameter | Value (Reference) | | | |
|---|---|---|---|---|
| | (26) | (29) | (30) | (31) |
| pH | 6,56 | 5,21 – 6,36 | - | 5,34 |
| Dissolved Oxygen,mg/L | 4,69 | 2,57 – 4,13 | - | 1,25 |
| COD, mg/L | 1806,33 | 1231 – 2422 | 42900 – 88250 | 284,79 |
| SS, mg/L | - | - | 14,1 – 26,4 | - |
| VSS, mg/L | - | - | | - |
| TSS, mg/L | - | - | 29,6 – 55,4 | 517,11 |
| VS, g/L | - | - | - | - |
| Conductivity, µS/cm | - | - | - | 2,51 |
| BOD, mg/L | 382,93 | 254 – 1541 | 17000 – 26700 | 123,68 |
| $SO_4$, mg/L | - | - | - | 65,75 |
| $NO_3$, mg/L | - | - | - | 262,26 |
| K, mg/L | 19,64 | 9,53 – 29,14 | 1281 – 1928 | 295,74 |
| Mg, mg/L | - | - | 254 – 344 | 283,46 |
| Na, mg/L | - | - | - | 332,26 |
| Ca, mg/L | - | - | 276 – 405 | 252,41 |
| Al, mg/L | - | - | - | - |
| B, mg/L | - | - | - | - |
| N, mg/L | 12,87 | 7,6 – 20,7 | - | - |
| P, mg/L | 8,18 | 5,26 – 8,68 | - | 165,65 |
| Cd, mg/L | 0,03 | 0,01 – 0,02 | 0,01 – 0,02 | - |
| Cu, mg/L | 2,44 | 0,6 – 1,61 | 0,8 – 1,6 | - |
| Fe, mg/L | 5,62 | 1,8 – 13,8 | 75 – 164 | 183,49 |
| Cr, mg/L | 2,01 | 0,61 – 1,68 | 0,05 – 0,43 | - |

| Parameter | Value (Reference) | | | |
|---|---|---|---|---|
| | (26) | (29) | (30) | (31) |
| Zn, mg/L | - | - | 1,2 – 1,8 | 120,95 |
| Mo, mg/L | - | - | - | - |
| Mn, mg/L | - | - | 2,1 – 4,4 | 34,25 |
| Ni, mg/L | - | - | - | - |
| Si, mg/L | - | - | - | - |
| Ba, mg/L | - | - | - | - |
| Co, mg/L | - | - | 0,04 – 0,06 | - |

The high concentration of carbohydrates, proteins, nitrogenous compounds, lipids and minerals found in POME makes it impossible to reuse without proper treatment. POME can cause environmental pollution due to oxygen depletion, soil pollution and other related effects. The discharge of POME in aquatic ecosystems turns the water brown, smelly, and slimy, can kill fish and aquatic organisms, and makes it difficult for residents to access clean water. In addition, it also pollutes soils and ecosystems, leading to loss of land resources and biodiversity (32).

### *2.1.2 Biogas*

Biogas consists mainly of methane ($CH_4$) and carbon dioxide ($CO_2$), with a methane content ranging from 50% to 75% (33). In comparison, raw biogas with a methane content of about 60% only has a heating value of about 21.5 MJ/m$^3$ (33). In contrast, carbon dioxide, which typically accounts for 25-50% of biogas, does not contribute to the heating value and must be removed through the purification process to enable more efficient use of the biogas (34,35).

**Table 2.** Biogas Composition and Properties (11,33)

| Component | Concentration | Properties |
|---|---|---|
| Methane ($CH_4$) | 50 – 75 vol% | Energy carrier |
| Carbon Dioxide ($CO_2$) | 25 – 50 vol % | Low heating value, causes corrosion, and makes the environment humid. |
| Hydrogen Sulfide ($H_2S$) | 0 – 4000 ppm | Corrosive, emits $SO_2$ gas while combusting. |
| Ammonia ($NH_3$) | ~ 1000 ppm | Emits $NO_x$ gas while combustion |
| Nitrogen ($N_2$)_ | ~ 0,2 vol % | Low heating value |
| Water Vapour ($H_2O$) | 1 – 5 vol % | Enhances corrosion combined with $CO_2$ and $SO_2$ |
| Hydrogen ($H_2$) | 10 – 60 ppm | - |
| Oxygen ($O_2$) | ~ 0 | - |
| Other Hydrocarbon | ~ 0 | - |

### *2.2 Methods*

The methodology employed in the development of this journal involved a systematic approach to gathering relevant information through an extensive review of existing literature, academic publications, and empirical studies. This process included the identification, selection, and critical examination of credible sources related to the subject matter. Following the data collection phase, a comprehensive analysis was conducted to synthesize findings, draw comparisons, and identify patterns or gaps within the available body of knowledge. This method ensured that the conclusions presented in this journal are grounded in well-documented research and supported by evidence-based insights

## 3. Results

Based on multiple literature study, it is found that POME utilization for biogas production can be increasingly enhanced by optimizing several key operational parameters, including temperature, anaerobic reactors, co-digestion technique, and biogas upgrading technology

### *3.1 Temperature*

Temperature is one of the primary factors that determines the activity and survival of microorganisms involved in the AD process. There are three main temperature ranges in AD, namely psychrophilic (<20°C), mesophilic (25-40°C), and thermophilic (50-65°C) (50-52). Mesophilic and thermophilic systems are the most commonly used; thermophilic systems offer advantages such as faster reaction rates and higher pathogen destruction capabilities. However, high temperatures can also cause bottlenecks such as ammonia inhibition and volatile fatty acid (VFA) accumulation that can decrease gas production (53-56). Process stability in mesophilic systems is generally higher than in thermophilic systems, owing to a stronger bacterial consortium and better resistance to environmental changes. However, mesophilic systems often require longer residence times and produce lower amounts of methane. Optimization of the operating temperature, particularly through the transition from mesophilic to thermophilic conditions in anaerobic co-digestion, has been shown to significantly increase biogas production.

**Table 3.** C/N Ratio for Several types of substrate (50,57–59)

| Substrat | C/N Ratio |
|---|---|
| Cow Manure | 16 – 25 |
| Poultry Manure | 5 – 15 |
| Goat Manure | 10 – 17 |
| Horse Manure | 20 – 25 |
| Kitchen Waste | 6 – 14 |
| Fruit and Vegetable Waste | 7 – 35 |
| Food Waste | 3 – 17 |
| Mixed Food Waste | 15 – 32 |
| Peanut Waste | 19 – 32 |
| Sheep Manure | 20 – 34 |
| Municipal Waste | 21 – 36 |
| *Palm Oil Mill Effluent* (POME) | 25 – 50 |

Nutrient balance (C/N Ratio) also plays an important role in supporting microorganism activity. Nutrient imbalance can lead to suboptimal anaerobic decomposition and a decrease in methane yield, particularly in mesophilic systems. Additionally, the residence time of organic matter in the digester has a direct impact on the process's efficiency. Thermophilic systems allow for shorter residence times, but need to be balanced with control of process parameters to maintain methane yields (60-62).

### *3.2 Anaerobic Reactors*

Anaerobic reactors are essential in biogas systems, with different types suited to specific conditions. Single-stage reactors efficiently convert organic matter by combining acidogenesis and methanogenesis, handling high organic loads and short retention times (63). Batch reactors are simple and low-cost but offer lower efficiency and intermittent biogas production, with only 54.4% methane recovery over 20–30 days (64, 65). UASB reactors manage high loads with low energy use but are sensitive to shocks and best for low-strength effluents; a 2-stage UASB can reduce retention time to 15 days (66–68). Plug-Flow Reactors (PFRs) improve solids retention and treatment efficiency but face mixing challenges and higher energy needs (69). Innovations like effluent recycling, co-digestion, pre-treatment, and improved impeller designs enhance biogas yield and system performance (70).

### 3.3 *Anaerobic co-digestion*

Anaerobic co-digestion is a process that simultaneously digests different types of organic matter, utilising their complementary properties to enhance the overall efficiency of biogas production. This approach not only expands the types of substrates that can be used but also significantly increases the total volume of biogas production (71). The use of various substrates also expands the diversity of the bacterial population, potentially enhancing the efficiency of organic matter degradation (12, 77, 78).

**Table 4.** Several Research on *Co-digestion*

| Substrat | Co-Substrat | Biogas Rate (L/day) | Methane Yield (L/kg VS) | Description | References |
|---|---|---|---|---|---|
| Cow Manure | Olive oil waste | 1,10 | 179 | Enhanced biogas production up to 33.7% | (79) |
| Cow Manure | Energy Crop Waste | 2,70 | 620 | Enhanced biogas production | (80) |
| Fruit and Vegetable Waste | Waste water and Slaughterhouse | 2,53 | 611 | Enhanced biogas production up to 51.5% | (81) |
| Municipal Solid Waste | *Fly Ash* | 6,50 | 222 | Enhanced rate of biogas production. | (82) |
| POME | Cow Manure | - | 2462 | Addition of additives (OHP and $NH_4HCO_3$) | (83) |
| Sludge | Municipal Solid Waste | 3,00 | 532 | Enhanced rate of biogas production. | (84) |

However, despite its many benefits, anaerobic co-digestion also faces its challenges. The costs associated with collecting, transporting, and pre-treating different types of substrates can be quite high, limiting their feasibility under certain conditions. Additionally, operational issues such as pump and pipe blockages, as well as scale formation in the digester tank, can hinder the process's efficiency. Various studies have shown that co-digestion can increase biogas yield; for example, the addition of fly ash to municipal solid waste significantly improves biogas conversion (85).

### *3.4 Biogas Technology Upgrading*

The biogas upgrading process is a crucial step in enhancing the quality of biogas by removing impurities, such as carbon dioxide ($CO_2$), hydrogen sulphide, and water vapour, which aim to increase the heating value of the gas and meet certain usage standards (86). Various upgrading technologies are available, ranging from conventional methods such as pressure swing adsorption, water scrubbing, and amine scrubbing, to newer technologies like cryogenic and membrane separation, each with its advantages and limitations (87). The choice of upgrading technology depends on factors such as utilization area, operational cost, and efficiency of the upgrading process (88).

**Table 5.** Evaluation of Alternative Biogas Upgrade method (91–93)

| | Cryogenic | *PSA* | Water Scrubbing | Physical Scrubbing | *Chemical Absorption* | Membrane Separation |
|---|---|---|---|---|---|---|
| Biogas Consumption ($kWh/Nm^3$) | 0,76 | 0,23 – 0,30 | 0,25 – 0,30 | 0,20 – 0,30 | 0,05 – 0,15 | 0,18 – 0,20 |
| Biomethane Consumption ($kWh/Nm^3$) | NA | 0,29 – 1,00 | 0,30 – 0,90 | 0,40 | 0,05 – 0,25 | 0,14 – 0,26 |
| Energy Consumption ($kWh/Nm^3$) | NA | - | - | < 0,20 | 0,50 – 0,75 | - |
| Temperature Requirement (°C) | -196 | - | - | 55 – 80 | 100 – 180 | - |
| Cost | High | Medium | Medium | Medium | High | High |
| $CH_4$ Losses (%) | 2 | < 4 | < 2 | 2 – 4 | < 0,10 | < 0,6 |
| $CH_4$ Recovery (%) | 97 – 98 | 96 – 98 | 96 – 98 | 96 – 98 | 96 – 99 | 96 – 98 |
| Pre-Treatment | Yes | Yes | Recommended | Recommended | Yes | Recommended |

| | **Cryogenic** | ***PSA*** | **Water Scrubbing** | **Physical Scrubbing** | ***Chemical Absorption*** | **Membrane Separation** |
|---|---|---|---|---|---|---|
| $H_2S$ Co-Removal | Yes | Possibly | Yes | Possibly | ContaminanT | Possibly |
| $N_2$ & $O_2$ Co-Removal | Yes | Possibly | No | No | No | Partial |
| Operating Pressure(bar) | 80 | 3 – 10 | 4 – 10 | 4 – 8 | Atmospheric | 5 – 8 |
| Outlet Pressure (bar) | 8 – 10 | 4 – 5 | 7 – 10 | 1,3 – 7,5 | 4 – 5 | 4 – 6 |
| Capital Expenditure ($/Nm$^3$ biogas) | - | 0,45 | 0,15 | 0,23 | 0,14 | 0,19 |
| Maintenance Cost ($/year/1000 m$^3$ biogas) | - | 15.000 | 39.000 | 59.000 | 56.000 | 25.000 |

The efficiency of upgrading technologies is evaluated based on several criteria, including operation and maintenance costs, capital expenditure (CAPEX), methane recovery, and methane losses during the upgrading process (94). For example, membrane technology has lower operating costs than chemical absorption methods, but requires a higher initial investment (95).

## 4. Discussion

Many studies show significant enhancement in biogas production and process optimization, particularly when utilizing organic waste streams such as Palm Oil Mill Effluent (POME). POME has limitations that hold them from being implemented thoroughly in biogas production, such as high chemical oxygen demand (COD), biological oxygen demand (BOD), and the potential for process instability due to its high organic and suspended solids content. However, POME still holds considerable potential as a feedstock for anaerobic digestion. Through systematic optimization, POME can be transformed into a more commercially viable resource for renewable energy production. One of the most critical parameters in this optimization is temperature control (50-62). Additionally, recent advancements in pre-treatment technologies (e.g., thermal hydrolysis or acidification) and co-digestion strategies with other agricultural or municipal waste streams have shown to enhance the biodegradability of POME, leading to increased methane yields (83). Moreover, the application of biogas upgrading technologies such as pressure swing adsorption (PSA), membrane separation, or water scrubbing allows the raw biogas to be refined into high-purity biomethane (91-93). This upgraded biogas can then meet the quality standards required for grid injection or use as a vehicle fuel, thereby adding economic value and expanding its potential markets. The integration of optimal operating conditions, innovative digestor technologies, and biogas upgrading methods demonstrates great promise in overcoming the inherent limitations of POME and positioning it as a reliable and high-quality feedstock for sustainable biogas production

## 5. CONCLUSIONS

A major challenge in using POME for anaerobic digestion (AD) is the presence of contaminants, including gravel, soil, and sand, as well as other liquid compounds that can reduce the efficiency of the AD process and potentially lead to the termination of digester operation. Therefore, future efforts should focus on enhancing the POME feedstock separation method to improve the digestion process (97-99). Although POME-cow manure co-digestion has been applied and produced the largest methane yield of any co-digestion at 2462 L/kg VS, the stability of the AD process still requires further optimisation studies (100,101). In addition, enhanced microbial activity during AD can be obtained by the addition of micronutrients in the form of nanoparticles, which is an area of future research. On the biogas upgrading side, new hybrid technologies show potential to optimize the biogas upgrading process; however, further research is needed to explore the benefits of combining technologies, as well as optimize economic aspects (102,103). The management of methane losses during the upgrading process is also a significant concern, as methane lost as flue gas is a highly potent greenhouse gas. Therefore, future upgrading plant designs should be able to capture this methane to reduce environmental impacts (104-106). In terms of cost, a reduction in upgrading costs, especially for small-scale plants, is necessary, as the equipment required makes the cost relatively higher, particularly in rural areas. Therefore, research should be directed towards more economical solutions (107). Government support is also a crucial factor in encouraging biogas production and utilization, through policies such as subsidizing biogas vehicles, feed-in tariffs for biogas-based power plants, and household clean energy.

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