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Biogas Production from Palm Oil Mill Effluent and the Prospect of Co-digestion with Empty Fruit Bunches – A Comprehensive Review

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ABSTRACT

Palm oil mill effluent (POME) and oil palm empty fruit bunches (OPEFB) represent two major waste streams in the palm oil industry that pose serious environmental challenges but also offer significant opportunities for renewable energy generation. This review comprehensively discusses the development of biogas production from POME through anaerobic digestion (AD) and explores the prospects of co-digestion with OPEFB to improve system efficiency and sustainability. A systematic literature survey of over 150 publications from the past four decades was conducted to evaluate technological evolution, operational parameters, methane yield, and environmental implications. The review identifies five major phases of POME biogas development—from early feasibility studies in the 1980s to the current exploitation phase integrating energy recovery, carbon credit schemes, and circular bioeconomy principles. Anaerobic digestion of POME in covered lagoon systems has achieved COD removal efficiencies exceeding 90% and methane yields of 0.28–0.34 Nm³ CH_4 per kg COD removed, supporting electricity generation potentials above 1 GW nationwide. Meanwhile, co-digestion with OPEFB enhances process stability, optimizes the C/N ratio, and improves methane production by 20–40% depending on substrate ratio and pretreatment. The integration of POME–OPEFB co-digestion can substantially reduce greenhouse gas emissions and provide value-added biofertilizers, thereby strengthening the environmental and economic sustainability of palm oil mills. Despite technological advances, several challenges remain, including high investment cost, OPEFB pretreatment, and limited policy support for grid connection. Further development of scalable, low-cost digesters and biogas upgrading systems is essential to realize the full potential of biogas as a renewable energy pathway within the palm oil sector.

1. INTRODUCTION

Oil palm has been attaining increasing reputation as a cash crop in several tropical countries. Indonesia is the largest palm oil producer in the world, with a contribution reaching >60%. The Indonesian palm oil industry is still growing. In recent decades, the palm oil industry has become one of the important economic sectors in Indonesia. The palm oil industry in Indonesia has plantations reaching 14.9857 million hectares in 2023, with a production of 45.5809 million tons of CPO (crude palm oil). Palm oil exports in 2022 have reached 26.24 million tons, down from 29.30 million tons in 2018. However, the export value in 2022 reached 29.66 billion USD, much higher than 17.90 billion USD in 2018 (BPS, 2023). The palm oil industry is one of the pillars of the Indonesian economy, contributing greatly to the country's GDP (Gross Domestic Product) and providing jobs to millions of people, both directly and indirectly.

The oil palm industry is one of the most important agricultural sectors, particularly in Southeast Asia, contributing significantly to global edible oil production. The palm oil industry plays an important role in the economic development of the countries. However, this industry is also associated with considerable environmental challenges, primarily due to the large amounts of waste generated during palm oil production. Two of the most prominent waste products are Oil Palm Empty Fruit Bunches (OPEFB) and Palm Oil Mill Effluent (POME). These by-products, if not properly managed, contribute to environmental pollution, including greenhouse gas (GHG) emissions, water contamination, and the loss of potentially valuable resources. Aziz & Hanafiah (2020) asserted that POME-derived biogas is a promising technology to meet not only the national goals on renewable energy share, but also to reduce greenhouse gas emission.

OPEFB, a lignocellulosic biomass, constitutes a significant portion of the solid waste produced during the palm oil extraction process. The large quantities of OPEFB generated pose disposal challenges due to its bulky nature and slow biodegradation rate. On the other hand, POME, which is produced in vast quantities during oil extraction and refining, contains high levels of organic matter and has a high chemical oxygen demand (COD) and biological oxygen demand (BOD). Untreated POME can cause severe water pollution and emit methane, a potent GHG, into the atmosphere.

The growing concern over environmental sustainability in the palm oil industry has led to increasing interest in waste valorization strategies. Waste reduction enhance profitability and circular economy of palm oil industry (Siagian *et al*., 2024). Co-digestion, which involves the simultaneous anaerobic digestion of two or more substrates, has emerged as a promising approach for addressing these waste management challenges. By co-digesting OPEFB and POME, the anaerobic digestion process can be optimized to improve biogas yield, reduce waste volume, and produce valuable by-products such as biofertilizers. This process not only minimizes the environmental footprint of the palm oil industry but also contributes to renewable energy generation, thereby supporting the transition to a circular bioeconomy.

This review paper aims to explore the potential of co-digestion of OPEFB and POME to improve the sustainability of the oil palm industry. It will focus on the biochemical and operational aspects of co-digestion, the optimization of process parameters, and the environmental and economic benefits of this integrated waste management approach. Additionally, this paper will discuss challenges associated with co-digestion, including technical limitations and regulatory hurdles, while highlighting potential solutions and future research directions.

2. RESEARCH METHODOLOGY

The databases used to prepare this review paper were collected from highly reputable journals published by Elsevier (www.sciencedirect.com), Springer (www.springerlink.com) and Wiley (www.wiley.com). Google Scholar was also used to identify local journal papers and conference proceedings, especially studies presented in Bahasa Indonesia, which are also important due to a fact that Indonesia is a leading country producing crude palm oil (CPO). The search for papers was conducted using several key words, such as ‘POME treatment technology’, ‘EFB current treatment,’ and ‘co-digestion of POME+EFB’, which yielded a wide range of literature sources. The selection of the literature to be included in this paper was based on careful analysis of the title, abstract, keywords and discussion of the research paper. Approximately 160 research papers have been selected for this review with a range span from 1980 - 2025. Only peer-reviewed papers and official reports were included.

3. RESULTS AND DISCUSSION

3.1. Oil Palm Processing

Palm oil extraction is a collection of process steps that aim to separate CPO from FFB. The palm oil extraction process consists of several stages (Ma & Ong, 1985; Pahan, 2011), namely: (1) Receiving of raw materials, namely fresh fruit bunches (FFB) in the loading ramp area of the palm oil mill. (2) The FFB sterilization process uses hot steam at a temperature of 135-150 °C and a pressure of 2.5-3 atm for 75-90 minutes. Sterilization has two main objectives, namely stopping the activity of enzymes that damage oil by forming free fatty acids (FFA), and facilitating the process of threshing oil palm fruit from its bunches. (3) Threshing or stripping, is the process of separating oil palm fruit (nuts) from the bunches using a rotating drum thresher unit. In this thresher, FFB is lifted and dropped repeatedly, so that the oil palm fruit is released from the bunch. (4) The crushing process (digestion) is carried out in the crushing unit (digester) by means of hot steam at a temperature of 85-95 °C which is injected directly into the fruit and pulp of the palm fruit. This crushing process aims to separate the mesocarp from the seeds and destroy the cells containing oil in the mesocarp. (5) The pressing process of the crushed mesocarp occurs in a twin screw extractor unit at a pressure of 50 kg/cm^2 for 6-10 min. Hot water at a temperature of 85-90 °C is added to the pressing process to facilitate the removal of oil from the mesocarp cells. (6) The clarification process is the processing of crude oil palm (CPO) that comes out of the pressing. This crude oil is a mixture consisting of oil (CPO) (35-45%), water (45-55%), fiber and other solids. This mixture is pumped into a clarification tank at a temperature of 90 °C to separate the oil from the other parts. The oil comes out through the upper clarification channel, is pumped to the centrifugation and vacuum drying unit, and then sent to the storage area. The CPO produced from clarification, centrifugation, and drying has a water content and impurities content of less than 0.1%.

The crude palm oil (CPO) extraction process requires quite a lot of water, reaching an average of 1.5 m^3/ton of FFP processed (Liew *et al*., 2015; Tabassum *et al*., 2015). Figure 1 shows a flow diagram and mass balance for the crude palm oil (CPO) extraction process in a palm oil mill (POM) with typical capacity of 60 ton FFB per hour. The calculations made in the diagram show that the palm oil processing produces CPO, which is the main product, amounting to 22.5% of the initial weight of the processed FFB.

3.2. Palm Oil Processing Waste

In addition to the main product CPO, the palm oil industry also produces solid waste such as OPEFB, fiber, shells, and boiler ash. The OPEFB waste is the most abundant solid waste (ca. 22%). In addition, the palm oil industry also produces wastewater of around 60% to 80% of the weight of the processed OPFFB. Table 1 shows the types of waste from palm oil processing and their typical proportions.

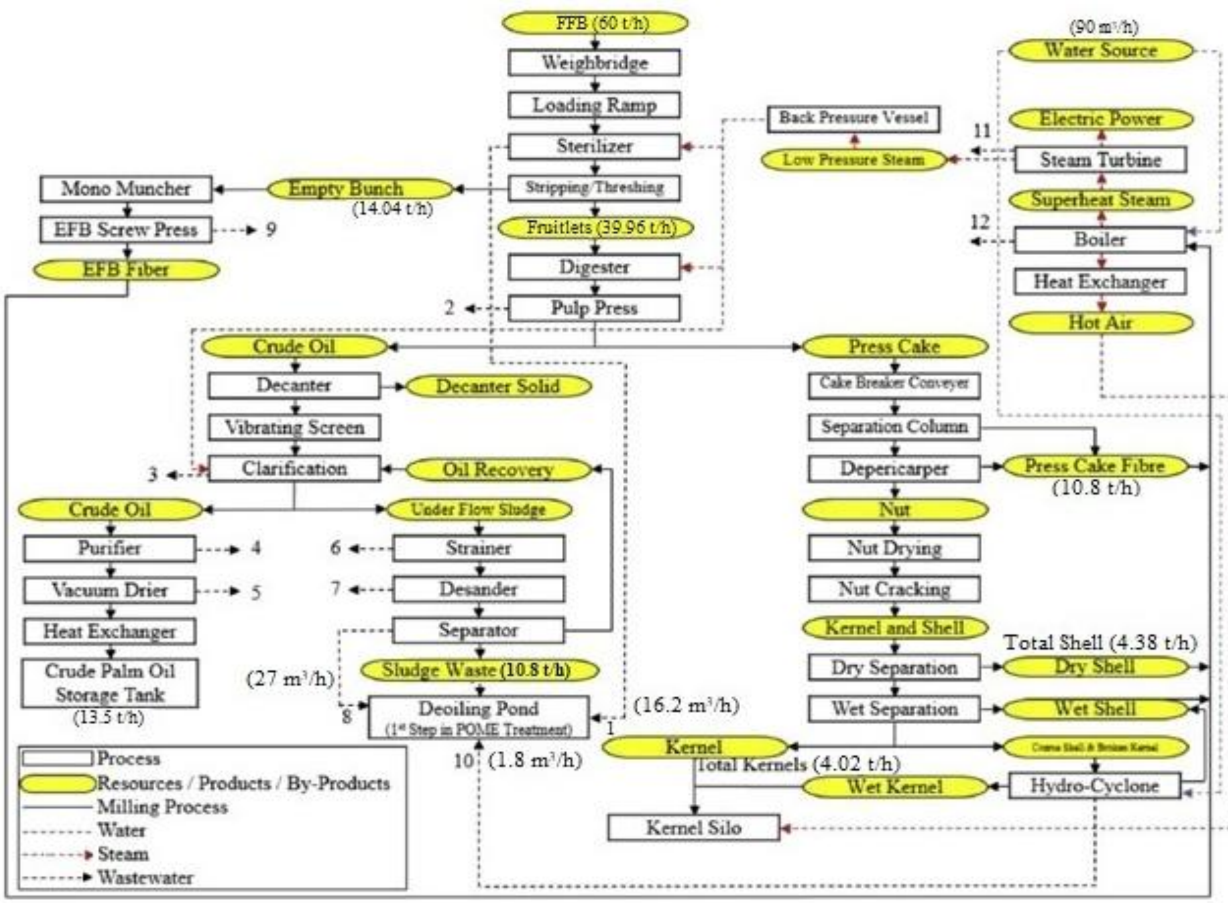

Figure 1. Diagram and mass balance of palm oil processing for a capacity of 60 t FFB/h [modified from Liew *et al*. (2015)]

Table 1. Types of wastes from the palm oil processing industry and their proportions

No	Waste type	Proportion	Reference
1	Empty fruit bunch (% FFB)	22-23	(Haryanto *et al*., 2021; Rassman *et al*., 2023)
2	Mesocarp Fiber (% FFB)	12-13	(Haryanto *et al*., 2021; Rassman *et al*., 2023)
3	Shell (% FFB)	5-6	(Haryanto *et al*., 2021; Rassman *et al*., 2023)
4	POME (m^3/ton TBS)	0.6-0.8	(Haryanto *et al*., 2021)
5	Boiler ash (% FFB)	3.36-4.12	(Nuryadi *et al*., 2019)

3.3. Palm Oil Mill Effluent (POME)

3.3.1. POME Characteristic

The CPO extraction process requires large amounts of water, resulting in large amounts of wastewater. Generally, 1.0 tons of OPFFB produces between 0.5 - 1.0 m^3 of wastewater. Palm oil mill wastewater is a mixture of wastewater originating from five processes , namely: (i) OPFFB sterilization (in the form of condensate water of around 36%), (ii) threshing, (iii) crushing and pressing, (iv) clarification and purification of CPO (contributing around 60% wastewater), and (v) the hydro-cyclone process (contributing around 4% wastewater) (Liew et al., 2015). The characteristics of wastewater produced from each stage of the palm oil extraction process can be observed in Table 2. Table 3 shows the composition of palm oil industry wastewater popularly called as POME (palm oil mill effluent) before being processed at a wastewater treatment plant, which is virtually a thick brown oily liquid with a temperature of 80-90 °C.

Table 2. Characteristics of wastewater from each stage of CPO production (Thani *et al*., 1999; Wu *et al*., 2010)

Parameter*)	FFB Sterilization	Clarification & Purification	Hydro-cyclone Process
pH	5.0	4.5	--
Oil and fat	4,000	7,000	300
BOD (3 day, 30°C)	23,000	29,000	5,000
COD	47,000	64,000	15,000
Total suspended solid (TSS)	5,000	23,000	7,000
Total dissolved solid (TDS)	34,000	22,000	100
Nitrogen Ammonia (AN)	20	40	--
Nitrogen Total (TN)	500	1,200	100

*) Note: All parameters are presented in mg/L, except pH (no unit)

Table 3. POME composition before treatment in wastewater treatment plant (Thani *et al*., 1999)

Parameter	Average value	Range	Minerals	Average
pH	4.3	4.4-5.2	P	180.0
Oil and fat	6,000	150-18,000	K	2,270.0
BOD (3 day, 30 °C)	25,000	10,000-44,000	Mg	615.0
COD	50,000	16,000-100,000	Ca	440.0
Total Solids (TS)	40,500	11,500-79,000	Bo	7.6
Total Volatile Solid (TVS)	34,000	9,000-72,000	Fe	47.0
Soluble Solids (SS)	18,000	5,000-54,000	Mn	2.0
Nitrogen Ammonia (AN)	35	4-80	Cu	0.9
Nitrogen Total (TN)	750	80-1,400	Zn	2.3

*) Note: All parameters are presented in mg/L, except pH (no unit)

Based on the nutrient content in POME that has been processed in anaerobic ponds, the wastewater is very beneficial for plants. Considering that wastewater from palm oil industry contains organic matter and does not contain hazardous and toxic materials, its utilization will not cause problems, in fact, it will provide benefits for oil palm plantations. To reduce the level of contamination, several stages of processing are carried out on palm oil mill wastewater so that it meets the wastewater quality standards set by the government. Generally, the processing of palm oil mill wastewater is carried out using an anaerobic biological system followed by facultative and aerobic biological. Considering the nutrient content in wastewater which is very good for plant growth, plant water requirements, and the difficulty of the IPAL system in producing wastewater that meets the quality standards for palm oil mill wastewater, after undergoing wastewater treatment, it is then used to water/irrigate oil palm plants with a special method (land application).

3.3.2. Utilization of POME (Existing)

Currently, most POMs (>85%) generally process POME using a series of open ponds, which is inexpensive, has a low operational maintenance, has a simplicity and ease of handling (Zainal *et al*., 2018). Treating POME using a series of open ponds (Figure 2a), also known as ponding systems, is widely practiced method, especially in regions where land availability is less of a concern. In this system, the effluent is treated through a series of ponds, typically including anaerobic, facultative, and aerobic and aerated ponds (Chan & Chong, 2019). Cooling and mixing pond serves to stabilise the POME temperature and pH prior to the anaerobic digestion. The anaerobic ponds allow microorganisms to break down the organic material in the absence of oxygen, significantly reducing the effluent's Biological Oxygen Demand (BOD). Anaerobic stage produces methane gas which is a value-added product after capturing for biogas. Facultative and aerobic ponds are necessary to further reduce the organic content in the wastewater before it is discharged to rivers (Zainal *et al*., 2018). The subsequent facultative and aerobic ponds further purify the effluent by allowing oxygen-dependent organisms to complete the decomposition process. This method is cost-effective and relatively simple to operate, making it an attractive option for many palm oil mills. In addition, the energy demand consumption for ponding systems is low due to the absence of mechanical mixing and rarely operation control or monitoring (Jumadi *et al*., 2020). The ponding system has been found to show a productively reduced the concentration of pollutants up to 100-1725 mg/L for COD, 100-610 mg/L for BOD and 100-200 mg/L for ammoniacal nitrogen (Chin *et al*., 1996; Zahrim *et al*., 2014).

However, open pond systems come with notable disadvantages. Formation of scum (Figure 2b) and the accumulation of solid sludge at the bottom of the pond is considering one shortcoming of the treatment (Jumadi *et al*., 2020). Other main issues is that the process is slow that takes very long hydraulic retention times. Therefore, this method requires large land areas, making it less suitable for mills located in land-scarce regions. It takes around 5 ha for a POM which has a capacity of 30 tons FFB/h (Leela & Nur, 2019). The open nature of the ponds also poses a risk of GHG emissions, particularly methane, which is a potent contributor to climate change (Choong *et al*., 2018; Zainal *et al*., 2018). In general, open ponding is a low-cost option in terms of capital and operation. However, this traditional approach is losing appeal as the methane generated escapes into the atmosphere, making it ineligible for Carbon Emission Reduction credits (Wu *et al*., 2010). A study in Malaysia reported that a palm oil mill operating in 277 days/year was capable of milling 174,190 tons of FFB, producing 85,834 tons of POME and methane emissions of 1125.22 tons/year (Yacob *et al*., 2006). Another study reported that measuring CH_4 emissions from anaerobic ponds of a POM with a capacity of 30 tons of

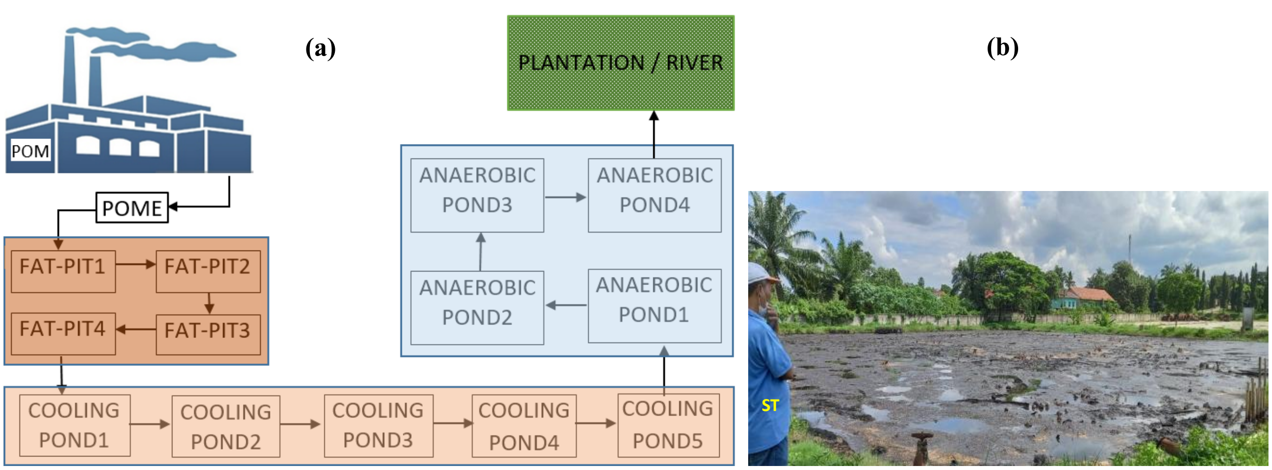

Figure 2. (a) Schematic of POME treatment plant, and (b) scum accumulated in the anaerobic pond of a POME treatment plant (Photo by Author: ST = Sugeng Triyono)

OPFFB per hour resulted in a relatively high CH_4 emission rate of 261.93 g/m^2/day, equivalent to 48.57 t CO_2-eq/day or 14,571.5 t CO_2-eq/year (Putro, 2022). Additionally, these systems are vulnerable to environmental factors, such as heavy rainfall or evaporation, which can affect the efficiency of the treatment process. Moreover, poor maintenance or improper design of the ponds can lead to water contamination, bad odors, and even overflow of untreated effluent, potentially causing harm to nearby ecosystems and communities.

The quantity of POME can be reduced by applying it for co-composting OPEFB. The amount of POME used in the co-composting process seems to be related to the composting method, OPEFB conditions, geographic location, and the duration of the composting process. Our observation on windrow co-composting OPEFB-POME in Pangkalan Bun, Central Kalimantan with a composting period of 30 days consumed 2.38 m^3/ton of POME (Haryanto *et al*., 2019), while a similar process in Lampung used 3 m^3/ton of OPFFB (Hasanudin et al., 2015). The aerated bunker composting method using shredded OPEFB consumed POME at a rate of 5.6 m^3/ton of OPEFB (Hasanudin & Haryanto, 2015). In addition, the reduction of GHG emissions from POME due to the use for OPEFB composting process under aerated bunker system is 200.68 kg CO_2e per ton of OPFFB or 81.97% in conditions where no leachate is discharged to the wastewater treatment plant, and 188.25 kg CO_2e per ton of OPFFB or 76.90% in conditions where 10% of leachate is recycled to the wastewater treatment plant (Hasanudin & Haryanto, 2015). Meanwhile, windrow co-composting OPEFB-POME is expected to reduce GHG emission by 35.92% and 53.22% for 30-day and 80-day, respectively (Haryanto *et al*., 2019).

3.3.3. POME-Based Biogas

In 2023, Indonesia produce 45.5809 million ton CPO. At a CPO yield of 23% (Susilawardani *et al*., 2022), this is equivalent to 198.2 million ton FFB. During CPO extraction, the process generate POME close to 158.5 million m^3. Tables 1 and 2 indicate that POME is organic with high pollutant content, such as COD and BOD, which are at risk of polluting the environment if not managed properly. The POME is currently treated using open ponds which is ineffective and releases a large quantity of GHG emissions. For wastewater effluents containing high concentration of organic carbon, such as POME, anaerobic digestion is the best treatment approach (Perez *et al*., 2001). Anaerobic digestion of POME offers a quicker return on investment by allowing biogas to be captured for energy use and producing treated effluent suitable for land application. The biogas production from POME treatment can sustain and ensure the palm oil industry to be more environmentally and economically sustainable (Khadaroo *et al*., 2019). POME treatment using covered lagoon achieved the highest removal efficiencies for COD, TSS, TVS, and lignin of >80% as compared to open pond systems with <50% removal (Yap *et al*., 2020). Therefore, the use of POME as a raw material for biogas is a strategic solution that not only reduces environmental impacts but also produces renewable energy. This approach is in line with decarbonization efforts, energy efficiency, and development of a circular economy in the agro-industrial sector.

According to (Menon, 2001), biogas production potential is roughly 14 m^3 for every ton of the processed FFB. Accordingly, the biogas potential is around 2.77 billion Nm^3 annualy. The biogas potential can also be predicted from POME quantity at a rate of 28 Nm^3/ton (Tong & Jaafar, 2006), resulting annual biogas production of 4.4 billion Nm^3. The most reliable prediction for biogas production should consider the organic loading rate as well as COD removal efficiency. The best anaerobic treatment for POME can reach the highest COD removal of 92% (Lok *et al*., 2020) or even 93.4% (Yong *et al*., 2023). For biogas production under covered lagoon aaerobic digester, which is the most adopted system, the efficiency up to 92% can be realized (Antoni *et al*., 2020). Based on POME characteristic in Table 2, it can be calculated that biogas potential of Indonesia from POME is 2.04 billion Nm^3. This potential can be explored to generate 1.1 GW electricity across 22 provinces (Setiawan *et al*., 2023; GREE, 2024) as presented in Figure 3. According to (Siregar *et al*., 2020) a POM with hourly capacity of 30 tons FFB can generate biogas of ±840 m^3/h or an energy equivalent of 5.208 kWh. Using gas engine with 35% efficiency, the equivalent of electrical energy is 1,822 kWh or or electrical power of 1.8 MW. The potential revenue with the same assumption is 12.8 billion IDR/year. At a CAPEX of 30-40 billion IDR, it can be expected that the pay-back period is 3-4 year. Afterwards, Afterward, POMs will reap economic benefits, especially since biogas facilities can last for a long time. In Malaysia, a biogas facility is reportedly still operating after 27 years of use (Tong & Lee, 2006).

According to (Kaewmai *et al*., 2013) Wastewater treatment facilities with and without biogas capture generated greenhouse gas emissions of respectively 64 and 47 percent of total emissions in palm oil industry. Therefore, the first step in lowering GHG emissions must be the installation of a biogas recovery system. GHG emissions might be lowered

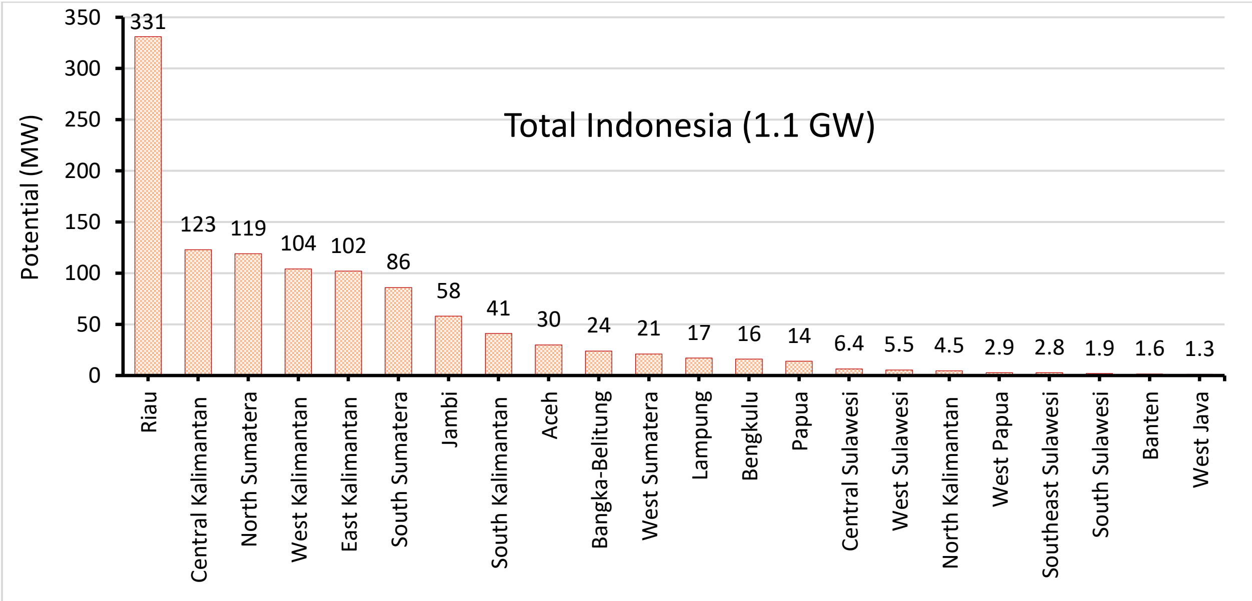

Figure 3. Electricity power potential generating from POME biogas in Indonesia (GREE, 2024)

by 373 kgCO_2eq/t of CPO. Capturing biogas from POME management is one way to realize a more environmentally friendly, cleaner production, and sustainable palm oil industries (Ahmed *et al*., 2015). The development of research to the application of biogas from palm oil industry waste can be divided into 5 phases, namely the early or initial phase (1981-1990), exploration (1991-2000), verification or validation (2001-2010), application or implementation (2011-2020), and exploitation (2020-present).

Early Phase (1981-1990)

Early research on using POME as a biogas substrate focused on demonstrating the feasibility and potential of this waste stream for biogas production. Major research themes during initial stage (1981-1990) involved: (1) Characterization of POME as a biogas substrate, (2) Evaluation of lab scale anaerobic processes in general, (3) Effect of operational parameters, and (4) Process stability and inhibition issues. Many early studies focused on analyzing the physicochemical properties of POME, such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Solids (TS), and Volatile Solids (VS). It was found that POME is very rich in organic matter with COD value more than 60,000 mg/L (Chin & Wong, 1983; Ng *et al*., 1985), making it a potential substrate for anaerobic processes. Anaerobic ponds have been used as an initial step in the treatment of POME and first-order kinetic rate coefficients (k) was found to be 0.36 day^{-1} (Wong & Springer, 1981). Research began to test the efficiency of anaerobic digestion in treating POME using simple reactors such as anaerobic ponds, anaerobic contact processes, or upflow anaerobic sludge blankets (UASB). The main focus was on reducing pollutant loads (COD/BOD) and methane gas production. Several important findings indicate that although POME can be treated without the addition of external nutrients at around neutral pH, and the process is more efficient under mesophilic conditions (30–40 °C) (Cail & Barford, 1985) or using two-phase anaerobic digestion system separating acidification and methanation phases (Ng *et al*., 1985; 1987). Early studies also explored the effects of temperature, pH, and residence time (HRT). It was reported, for example, that biogas production at an average rate of 0.9 L with an energy yield of 20 kJ was produced per gram BOD removed for units with solid retention time (SRT) >25 days (Chin, 1981). Another important finding is that to obtain high COD or BOD removal efficiency (>90%), the POME anaerobic digestion system requires a hydraulic retention time (HRT) of more than or equal to 15 days (Chin & Wong, 1983; Ma & Ong, 1988). At this stage, laboratory-scale experiments dominate the study and awareness of the energy potential of methane gas is still low. The main challenges found are pH fluctuations and the accumulation of volatile fatty acids (VFAs) that inhibit the activity of methanogenic microbes. This encourages further research on process stabilization and the role of microorganisms in the degradation of complex organic matter.

It is worthy to note that during this period two floating roof and one fixed roof tank digesters, each with a capacity of 2,500 m^3 (total capacity 7500 m^3) have been operating continuously at the Keck Seng Palm Oil Mill, at Masai, Johor, Malaysia, since 1984 (Chua, 1992). The system was operated for a 30 tFFB/h mill capacity at a POME flow rate of 400 m^3/day with COD loading rate of 2.6 to 3.5 kg/m^3/day and 18 days HRT. The resulting biogas at a rate 11,000 m^3/day contain 60% to 69% methane, and is utilized as fuel for steam boilers and high-pressure heaters in the palm oil refinery (Chua, 1992; Tong & Jaafar, 2006). Another POME treatment technology in the same company, namely Continuous flow Stirred Tank Reactor (KS-CSTR) with a capacity of 13,000 m^3/d has also been applied since 1984 in Johor to produce biogas (Tong & Lee, 2012).

Treatment in open ponds is still the main choice even though it requires a large area for pond construction. Until early of 1990s, 85% of POMs in Malaysia still adopted ponding system to treat their POME (Tong & Jaafar, 2006). POME treatment using ponds requires a long HRT, although it is the most affordable. For example, it is required a HRT of 67 and 1394 days to reduce POME with a BOD of 25,000 mg/L to 1000 and 50 mg/L, respectively (Ma, 1987). A theoretical methane emission for anaerobic POME treatment was established as the following (Shirai *et al*., 2003):

$$\text{Methane emission} = \text{CPO production} \times F1 \times F2 \times F3 \tag{1}$$

where F1 is POME yield factor in the CPO production, F2 is biogas yield factor from POME, and F3 is methane gas composition in the biogas mixture (%). Furthermore, (Shirai *et al*., 2003) recommended F1 valu of 2.5 m^3/t and F2 is 28 m^3/m^3. Considering the POME density, other F2 factor was proposed as 28.8 m^3/ton (Ee, 2009; Ma, 2002).

Exploration Phase (1991-2000)

The period of 1991–2000 can be said to be a phase of scientific exploration and validation of the POME potential as a biogas feedstock. During the 1991-2000 period, research on biogas production from palm oil mill effluent (POME) focused on optimizing anaerobic digestion processes and exploring the potential of biogas as a renewable energy source. Research during this decade became an important basis for the development of more advanced commercial biogas technology in the following decades. Key findings during this period confirmed that POME can produce biogas with a methane content of about 55–65%, which is comparable to other organic waste substrates. It is also highlighted the importance of proper pretreatment strategies, the impact of operating conditions like temperature and organic loading rate (OLR), and the need for biogas purification to remove impurities like hydrogen sulfide and carbon dioxide.

Some anaerobic digester types were also investigated with respect to POME, including Up-flow Anaerobic Sludge Blanket (UASB), Continuous flow Stir Tank Reactor (CSTR), Anaerobic Filter (AF), Fluidized-Bed Reactor (FBR), Covered Lagoon or CIGAR (Covered in the Ground Anaerobic Reactor), Anaerobic Baffled Reactor (ABR), and Membrane Anaerobic System (MAS). Table 4 provides a summary on the characteristic of some anaerobic digesters working with POME. Using 16-L UASB reactor running with COD load of 5.1 to 42.5 g/L and constant HRT of 4 days, it was reported that 96% COD removal was reported at COD loading rate of 10.6 g/L with methane yield coefficient of 0.325 L CH_4 STP per g COD removed (Borja & Banks, 1994a, 1994b). The same authors also reported the performance of AF and FBR is relatively inferior as compared the the UASB reactor (Borja & Banks, 1995). In addition, the performance of UASB reactor can be improved further by using two-step reactor configuration separating acidogenic and methanogenic stages (Borja *et al*., 1996). Performance of Covered Lagoon was reported by (Chin *et al*., 1996) where POME contains a high COD concentration (45,000 to 65,000 mg/L) was treated effectively to 1,725 mg/L under a system consisting of 8 ponds in series. The effects of recycle on the performances of ABR treating POME at a daily loading rate of 15.6 g COD/L was investigated with recycle variations from 5 to 25 times, and a recycle of >15 times is required to maintain the pH >6.8 without alkalinity adjustment (Setiadi *et al*., 1996). Meanwhile, in MAS was investigated to improve influent COD concentration from 39,910 mg/L 68,310 mg/L and is able to achieve COD removal efficiency of 91.7 to 94.2 percent with an average HRT of 3.03 days (Fakhru'l-Razi & Noor, 1999). In essence, the research during this period laid the groundwork for understanding the potential of biogas production from POME and paved the way for further advancements in biogas technology and its utilization as a sustainable energy source. (Ma, 1994) reported that anaerobic system consisting of two reactors to separate acidification and methanation was able to handle POME with loading rate of 1.5 kg/m^3 while achieving BOD removal efficiency of 98% within 20 days HRT. Further calculation shows that a POM with a capacity of 60 t/h (FFB) capable to produce biogas of 16,000 m^3/h, containing 65% methane, which corresponds to 9,600 L diesel fuel.

Table 4. Characteristic of some anaerobic reactors for POME treatment

Reactor type	COD loading ($kg/m^3/day$)	% COD removal	HRT (day)	Biogas yield (Nm^3)		CH4 (%)	Reference
				(/kgCOD$_r$)	(/tPOME)		
Anaerobic contact (45°C)	3.02*	94*	6.25	NA	17.5†	65	(Ibrahim *et al*., 1985)
Anaerobic open tank digester	2.16	80.7	20	0.37†	12.9†	36	(Yacob *et al*., 2005)
Anaerobic open pond	1.4	97.8	40	0.28†	15.52†	54.4	(Yacob *et al*., 2006)
UASB (Up-flow Anaerobic Sludge Blanket)	10.63	98.4	4	0.49†	20.57†	54.2	(Borja & Banks, 1994a)
UASFF (Up-flow Anaerobic Sludge Fixed-Film)	11.58	96.5	3	0.45†	16.27†	71.9	(Najafpour *et al*., 2006)
CSTR (Continuous Stirred Tank Reactor)	2.83	80–85	18.75	0.41†	28.3	62.5	Tong & Jaafar (2006)
Covered Lagoon‡	2.1	67–85	29–45	0.28	29	64.7–66.7	Yusof (2024); Lok *et al*. (2020)

*) In term of BOD; †) Calculated; ‡) Other name is CIGAR (Covered in Ground Anaerobic Reactor); NA = not available

Verification Phase (2001-2010)

In the period 2001-2010, water treatment technology has developed, and it is increasingly recognized that conventional POME treatments are seen to be outdated and unable to prevent GHG emissions into the environment, so that more efficient technologies are needed as well as being less cost-effective (Poh & Chong, 2009). Biogas generation based on POME become an attracting option. In the period 2000–2010, research on POME biogas shifted from scientific exploration to technology development and pilot-scale to industrial applications. This period marked an important transition point towards commercial utilization, driven by the increasing global attention to renewable energy and greenhouse gas emission reduction. Main research themes during this period consisted of: (1) anaerobic reactor efficiency improvement, (2) integration of waste treatment and renewable energy, (3) greenhouse gas emissions and Clean Development Mechanism (CDM) potential, and (4) industrial-scale research and demonstration. The focus of research shifted to the optimization of reactor technologies, such as the Upflow Anaerobic Sludge Blanket (UASB), Continuous Stirred Tank Reactor (CSTR), and Covered Lagoon system. Research emphasized the design of reactors that were more stable, resilient to load fluctuations, and efficient in capturing methane gas. Many studies began to discuss cogeneration (utilization of heat and electricity from biogas), as well as the integration of liquid and solid waste treatment systems in one energy production cycle. Researchers also reviewed the feasibility of bioenergy as part of a sustainable palm oil production system. There is increasing interest in the potential for methane emission reductions through biogas capture and utilization, following the implementation of the Kyoto Protocol as Certified Emission Reduction (CER) credits through CDM mechanism (Chin *et al*., 2006; Tong & Jaafar, 2006). It was calculated that during this period a total of RM2.6 million could be obtained from the selling of electricity generated from biogas generation and CER from 350 mills actively producing the CPO in Malaysia (Shirai *et al*., 2003). Studies have shifted to pilot-scale and industrial-scale, documenting the performance of biogas systems that have been operated in palm oil mills. Focuses include energy efficiency, potential cost savings, and operational challenges in the field.

Key findings during period of 2000–2010 highlight that UASB and covered lagoon reactors dominate application studies in the field with Covered Lagoon system recognized as the most suitable technology for palm oil mills in the Southeast Asia due to its low cost and simplicity, although its efficiency is lower than UASB. Some works refered Covered Lagoon system as CIGAR (Covered in Ground Anaerobic Reactor) (Yusof, 2024). Table 5 characterisize biogas generation from POME using Covered Lagoon system. Industrial systems with cooling towers and co-digestion recorded methane yield ~0.314 $Nm^3/kg\ COD_r$; while co-digestion with decanter cake reached biogas yield up to 0.379 $Nm^3/kg\ COD_r$ (Yusof, 2024). Improvement in COD removal efficiency is achieved up to >90% with a closed reactor system and good organic load control. Yacob *et al*. (2005) studied CH_4 emission in a POM based on 52 weeks measurement from 3600 m^3 open digesting tanks (HRT 20 days) where the CH_4 content was between 13.5% and 49.0% (average 36%). The biogas flow rate ranged between 0.8 and 9.8 $L{\cdot}min{\cdot}m^{-2}$ (average 5.4 $L{\cdot}min{\cdot}m^{-2}$). With 273 working days a year, the POM processed a total FFB 291,790 tonnes, released a total POME of 157,035 tonnes, and emited a total CH_4 of 518.9 kg/day per tank. It was calculated that 849 tonnes of CH_4 was released from 6 tanks to the atmosphere

Table 5. Feature of Covered-Lagoon anaerobic digesters treating POME

Parameter	Typical Range / Value	References
Organic Loading Rate (OLR)	≈ 1.2 – 1.6 kg·m^{-3}·day^{-1} (optimal 1.23 kg·m^{-3}·day^{-1})	(Yong *et al*., 2023)
Hydraulic Retention Time (HRT)	~20–30 days; commonly 30 days in covered lagoon systems	(Winanti *et al*., 2019)
pH	Raw POME (pH ~4.8) must be neutralized to ~7 via mixing with older effluent to support microbial stability	(Winanti *et al*., 2019)
Temperature	31.98–44.10 °C (average 39.35 °C)	(Yusof *et al*., 2024)
COD Removal Efficiency	85–98%; industrial plants showed 67–85%, some lagoon systems reached ~98.7%	(Okoro & Nwaiwu, 2016)
Biogas Yield	Around ~0.31 Nm^3/kg COD or 29 m^3/ton POME	(Lok *et al*., 2020)
Methane Content	Generally 60–66%	(Yusof, 2024)
Methane Yield	0.28–0.34 Nm^3 CH_4/kg COD_r	(Yong *et al*., 2023)

per year. During this observation an average COD of raw POME was 43,288±1924 mg/L, while the treated POME was 8327±2049 mg/L. Based on these figures the open digesting tank system was able to remove 34.9 kg of COD per 1 m^3 of POME, indicating approximately 80.7% of COD removal efficiency. In comparison, other study by (Yacob *et al*., 2006) reported emission from an open anaerobic ponds based on a year measurement that the methane content was between 35.0% and 70.0% (average 54%), biogas flow rate ranged between 0.5 and 2.4 L·min·m^{-2} (average 1.5 L·min·m^{-2}), and a total methane emission of 1043.1 kg/day per anaerobic pond. The values of methane content in the biogas released from both open laggon and open tanks are much lower than the reported value of 65% obtained by complete anaerobic condition of lab-scale experiments (Shirai et al., 2003). It is revealed that within a year the POM operates in 277 working days milled 174,190 ton FFB, produed 85,834 m^3 POME, and 1125.22 ton CH_4 emission. The COD values were 55,990±6126 mg/L for raw POME and 1204±292 mg/L for the treated POME, meaning a COD removal efficiency of 97.8%. It is concluded that anaerobic pond system is more efficient than open digesting tank system for POME treatment. Studies on biogas purification (upgrading) also begun to emerge, especially for the conversion of biogas to bio-CNG or biomethane. Further studies include economic feasibility studies and Life Cycle Assessment (LCA) have shown that biogas production from POME has the potential to significantly reduce energy costs and GHG emissions.

During this period, the implementation of the KS-CSTR anaerobic processing system was reported to have increased in several Keck Seng palm oil mills, including in Perak with a capacity of 13,000 m3/h (since 2006) and 35,000 m3/h (since 2009), as well as in Sabah (capacity 35,000 m^3/h, since 2008) (Tong & Lee, 2012). The introduction of CDM and the establishment of carbon funds are expected to attrack more POMs to implement anaerobic POME treatment, inspired by the success of mills that had previously registered such systems as CDM projects (Poh *et al*., 2010). The high cost of construction is a factor that inhibits the implementation of biogas capture technology.

Application or Implementation Phase (2011-2020)

The period 2010–2020 is a key phase in the real implementation of methane capture technology from POME through anaerobic processes in palm oil mills, especially in Indonesia and Malaysia. Key findings during this period (2010–2020) highlight the efficiency of methane capture reaches 60–85% of the total emissions produced by POME, with electricity production ranging from 500–2,000 kW per mill. LCA studies show that biogas from POME can reduce CO_2 emission by 1.5–3 tons of CO_2e per ton of POME processed. During this period, Malaysia took the lead in applying biogas capture to palm oil mills (POMs). In 2011, out of 426 POMs, 55 had biogas facilities and 16 more POMs were under construction (Chin *et al*., 2013). As presented in Figure 4*a*, the number of biogas plant had increased to 125 units in 2019 (Loh *et al*., 2020). Meanwhile, Indonesia followed suit slowly with the installation of a 1.0 MW biogas power plant (PLTBg) at POM PTPN V Tandun in 2012. After slow progress during 2006-2014 with a cumulative capacity of around 20 MW, the biogas plant in Indonesia boosted significantly during 2015-2020 period (Figure 4*b*) reaching a total capacity of more than 140 MW (Setiawan *et al*., 2023).

The implementation of biogas power plant, or PLTBg in short, based on POME in Indonesia has been started at 2012 by PTPN V Tandun with an installed capacity of 1.2 MW (Haryanto *et al*., 2012) for a mill capacity of 45 ton FFB/h

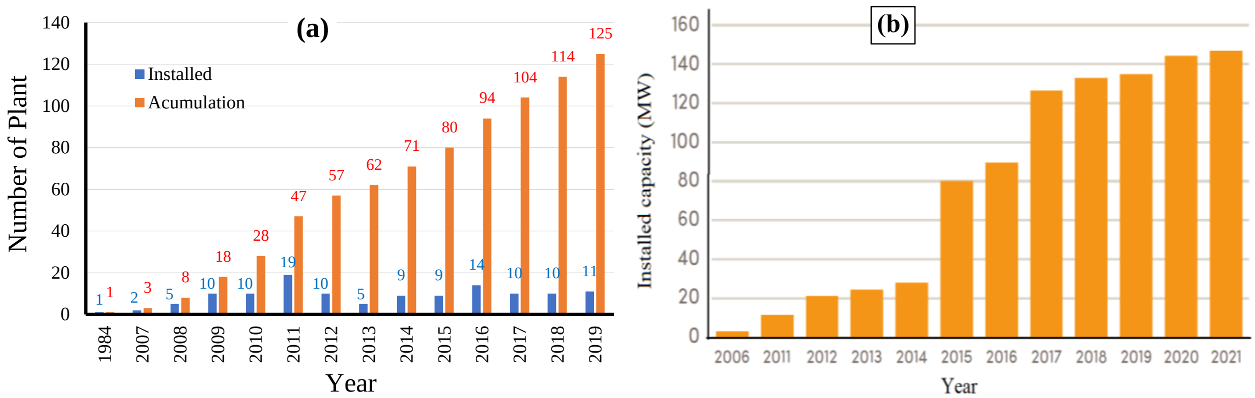

Figure 4. Progres of POME biogas plants: (a) Indonesia 2006-2021 based on capacity (Setiawan *et al*., 2023); (b) Malaysia based on number of plant (Loh *et al*., 2020).

(Pangarso & Kusdiyantini, 2022). The existence of this PLTBg has succeeded in reducing the cost of diesel fuel to IDR 5.8 billion per year. In addition, throughout 2020, the Tandun PLTBg also contributed to the addition of International Sustainability and Carbon Certification (ISCC) incentives of IDR 9.4 billion (GATRA, 2021). Recently, around 200 POMs in Indonesia and Malaysia are implementing methane capture systems (various anaerobic technologies + covered pond). The most likely system for biogas POME are covered lagoon and closed anaerobic digester tank.

During this period, research and policies began to focus on commercialization, system integration, and its contribution to national energy and GHG emission reduction. Main research themes during this period consisted of: (1) Implementation of methane capture in the palm oil industry, (2) Utilization of biogas for electricity and bioenergy, (3) Sustainability and environmental impact assessment, and (4) Policy and business model integration. Research has shifted towards real applications of biogas for internal power generation (captive power), injection into the grid (PLTMG/PLTBg), and conversion to bio-CNG. Additional focuses include energy efficiency, biogas quality, and genset performance. Many studies evaluate the impact of government policies (such as PERMEN ESDM and energy mix targets) and financing models for POME-based biogas projects. Donor support (GIZ, UNDP, WB) and incentive schemes such as feed-in tariffs are also discussed. Studies have focused on the evaluation and optimization of methane capture systems in palm oil mills, using covered lagoons, CSTRs, and UASBs, as well as documentation of the performance of biogas-based power generation systems from POME. Life Cycle Assessment (LCA) and carbon footprint studies assess the contribution of POME biogas projects to GHG emission reductions. POME is described as one of the important pathways for low-carbon energy transition in the agro-industrial sector.

During this period, there is a leap from research to widespread implementation driven by incentives and regulations. Further involvement of international institutions such as GIZ, UNDP, ADB, and IRENA, in many demonstration POME biogas projects and capacity development. Studies on the biogas purification technology including conversion to bio-CNG increase towards the end of the decade. With the increasing strength of the issue regarding environmental impact, LCA and carbon accounting become key elements in assessing sustainability. Biogas upgrading technology is developing with more systems using membranes, PSA (Pressure Swing Adsorption), and water scrubbing. Regulations in Indonesia (ESDM Regulation No. 12/2017) and Malaysia (Renewable Energy Act 2011) provide significant impetus for the development of biogas power plants. Malaysia and Indonesia have started to actively promote biogas projects as part of their green energy initiatives and have received funding from the CDM scheme. The CDM has become a driver of investment and technical research in Malaysia and Indonesia during the middle of this decade.

Exploitation Phase (>2021)

POME stands out as the largest and most promising feedstock for biogas production in Indonesia compared to other sources including municipal waste, manure, and cassava starch mill effluent. According to calculations by GIZ, biogas derived from POME has the potential to generate up to 1,290 MW of electricity –equivalent to 4.5 million m^3 of biogas or 2.7 billion m^3 of biomethane per year. This amount corresponds to approximately 2.4 billion liters of diesel or 1.8

billion kilograms of LPG. If biomethane were used to substitute that volume of diesel fuel or LPG, it could result in government savings of around IDR 5.6 trillion (Sukardi & Brata, 2021).

In the last two decades, the use of POME as a source for biogas has made significant progress, especially in major palm oil producing countries such as Indonesia and Malaysia. Anaerobic digester technology has begun to be widely applied, with support from the government, donor agencies, and the private sector. Despite its great potential, biogas production from POME still faces various challenges, such as high initial investment costs, issues of sustainable POME supply, and the complexity of managing and maintaining biogas installations. The utilization of biogas can be classified mainly into five, namely: (1) steam/heat and electricity generation, (2) solely for steam generation, (3) electricity production, (4) powering downstream business activities, and (5) flaring (Loh *et al*., 2017). Generally, about half of the biogas captured is for energy production whereas the other half of the plants opt to flare the gas. This issue has given rise to the idea of exploiting POME biogas into more manageable products that can be utilized off-site. During the exploitation phase (2021 and beyond), the biogas produced from anaerobic digestion of POME needs to be developed into a product that can be used elsewhere. Bottling biogas is one idea for more efficient transportation of biogas to other locations. Bottled biogas can be in the form of compressed biogas (CBG), biomethane, and bio-CNG. The first is to package biogas in a low pressure container that can be transported to other places (Yadav & Sutar, 2018). A 250-L volume plastic pouch can hold biogas for single-use light cooking. This is the easiest but impractical way to diversify the use of biogas. Biogas bottles like bottled LPG fuel. The question pertains to the options of either bottling or compressing biogas derived from POME. Both processes are viable, but each has its own set of considerations. Bottling involves filling purified biogas into cylinders, while compression increases the pressure and reduces the volume of biogas for easier transport and storage. The best option depends on the specific application and infrastructure available. Second, upgrading biogas into biomethane (Hoo *et al*., 2017). Third, upgrading biogas into Bio-CNG. Bio-CNG at its current state is too expensive for implementation where subsidies are required to enable the technology, especially for countries where energy price is low such as in Malaysia (Mohtar *et al*., 2017).

3.4. Empty Fruit Bunch (EFB)

Empty oil palm bunches (EFB) are produced from the stripping process that separates oil palm fruit into loose nuts. OPEFB is solid waste with the largest percentage produced from the CPO extraction process, which is around 20 – 23% (Abdullah & Sulaiman, 2013; Gandahi & Hanafi, 2014; Kerdsuwan & Laohalidano, 2011; Nabila *et al*., 2023). Thus, the biomass potential of OPEFB in Indonesia is equivalent to CPO production, which is around 45 million Mg/year. Table 6 summarizes physico-chemical properties of OPEFB. Without proper utilization, OPEFB will cause environmental problems because of its enormous amount. In addition, fresh OPEFB is wet with high water content up to 60% (Abdullah *et al*., 2011; Haryanto *et al*., 2019) that make difficult to manage. OPEFB is an organic material containing 42.8% C, 2.90% K_2O, 0.80% N, 0.22% P_2O_5, 0.30% MgO and micro-elements including 10 ppm B, 23 ppm Cu and 51 ppm Zn. Other important minerals are potassium (1.12%) and calcium (0.16%) (Lim *et al*., 2015). For every ton of EFB, there are nutrients equivalent to 3 kg of urea, 0.6 kg of RP (rock phosphate), 12 kg of MOP (muriate of potash), and 2 kg of kieserite (Singh *et al*., 1989).

3.4.1. Utilization of OPEFB (Existing)

In POMs with no plantation, OPEFB is normally burnt in an incinerator. This practice, though practical to be applied, is a cause of air pollution. So far, OPEFB is generally returned to the land as mulch to provide organic material for oil palm plantations with a dose of 37.5 tons/ha/year (Bakar et al., 2011; L. K. Chiew & Rahman, 1995). OPEFB mulch can improve vegetative growth, improve nutrients that can be absorbed by plant roots, and increase oil palm productivity. In addition, OPEFB mulch can also conserve soil moisture, reduce erosion, improve nutrient in the soil, lower soil surface temperature, and provide a slow release of nutrients over a long period of time (Iqbal *et al*., 2020). OPEFB will be stacked between rows of oil palm plants. Returning OPEFB to oil palm fields without treatment has several disadvantages that can negatively impact both the environment and agricultural productivity. Untreated OPEFB can retain excessive moisture, leading to waterlogging conditions in the soil. This can adversely affect root systems and contribute to poor aeration, ultimately harming plant health. OPEFB is also high in carbon and low in nitrogen, which can lead to nutrient imbalances in the soil. This imbalance can hinder plant growth and reduce soil fertility over time, as the decomposition of OPEFB may immobilize nitrogen, making it unavailable for plant uptake.

Table 6. Physico-chemical properties of EFB

Characteristic		Unit	Value	Reference
Bulk density		Mg/m^3	0.11	(Sung *et al*., 2010)
Calorific value		MJ/kg	15.82	(Haryanto *et al*., 2021)
Moisture content		%wb	40-65	(Haryanto *et al*., 2019)
Volatile matter		%db	27.08	(Iryani *et al*., 2019)
Fixed carbon		%db	63.61	(Iryani *et al*., 2019)
Ash content		%db	4-12	(Haryanto *et al*., 2021)
Oil content		%	3.5-12	(Ngan, 2005)
Physical compositions:	Main stalk	%	20-25	(Puasa *et al*., 2022; Lee & Ofori-Boateng, 2013)
	Spikelets	%	75-80	(Puasa *et al*., 2022; Lee & Ofori-Boateng, 2013)
Chemical compositions:	Cellulose	%db	18.2	(Sabil *et al*., 2013)
	Lignin	%db	33.2	(Sabil *et al*., 2013)
	Hemicellulose	%db	48.6	(Sabil *et al*., 2013)
Chemical elements:	Carbon (C)	%db	47.24	(Iryani *et al*., 2019)
	Hydrogen (H)	%db	6.63	(Iryani *et al*., 2019)
	Nitrogen (N)	%db	45.32	(Iryani *et al*., 2019)
	Oxygen (O)	%db	0.82	(Iryani *et al*., 2019)
Ash content:	Sulphur (S)	% ash	2.42–2.65	(Haryanto *et al*., 2021)
	Chlor (Cl)	% ash	4.52–6.45	(Haryanto *et al*., 2021)
	Phosphor (P_2O_5)	% ash	1.27–1.49	(Haryanto *et al*., 2021)
	Potassium (K_2O)	% ash	26.57–46.46	(Haryanto *et al*., 2021)
	Silica (SiO)	% ash	23.94–29.35	(Haryanto *et al*., 2021)
	Calcium (CaO)	% ash	9.14–17.07	(Haryanto *et al*., 2021)
	Iron (Fe_2O_3)	% ash	11.77–16.34	(Haryanto *et al*., 2021)
	Aluminum (Al_2O_3)	% ash	6.15–11.55	(Haryanto *et al*., 2021)
	Magnesium (Mg)	% ash	1.31–1.34	(Haryanto *et al*., 2021)
	Mangan (MnO)	% ash	0.67–0.465	(Haryanto *et al*., 2021)
	Sodium (Na)	% ash	0.033	(Shrivastava *et al*., 2021)

The natural decomposition of untreated OPEFB is slow due to its high lignocellulosic content. This slow breakdown can result in prolonged periods where nutrients are not readily available to plants, potentially stunting their growth. Piling untreated EFB can create a habitat for pests and diseases, especially as mating and breeding ground for rhinoceros beetle (Manjeri *et al*., 2014). Rhinoceros beetle (*Oryctes rhinoceros*) attack the growth points and is known as the most detrimental pest for oil palm. The accumulation of organic matter may attract rodents and insects, which can lead to infestations that affect oil palm health and yield. The decomposition of untreated organic matter can produce unpleasant odors and potentially leach harmful substances into the groundwater, affecting local water quality. The accumulation of OPEFB in fields can lead to environmental issues such as soil degradation and increased GHG emissions during the decomposition process if not properly managed (Haryanto *et al*., 2019). In summary, while returning untreated OPEFB to oil palm fields may seem beneficial for waste management, it poses significant risks to soil health, plant growth, pest management, and environmental sustainability. Proper treatment methods such as composting could mitigate these disadvantages by enhancing nutrient availability and reducing negative environmental impacts.

OPEFB can be applied as compost (Baron *et al*., 2019; Haryanto *et al*., 2019; Tahir *et al*., 2021; Zahrim *et al*., 2018) to replace chemical fertilizers in oil palm plantations. OPEFB compost has beneficial properties, including: (1) improving soil structure to be more porous; (2) helping the solubility of nutrients needed for plant growth; (3) homogeneous and reducing the risk of being a pest carrier; (4) is a fertilizer that is not easily washed away by water that seeps into the soil and (5) can be applied in any season (Darnoko *et al*., 1993). Although composting empty fruit bunches in aerobic conditions (Figure 4a and 4b) is more effective, this process requires a stirring machine (turner) and intensive labor (Kananam *et al*., 2011). The co-composting of OPEFB-POME is projected to cut GHG emissions by as much as 76% by preventing methane release from open dumping of OPEFB and POME treatment ponds, in addition to reducing the need for chemical fertilizers (Krishnan *et al*., 2017). Until now, most POMs do not have EFB composting units and still continue to practice the burning method or direct application to the land as mulch (Chiew & Shimada, 2013). Some OPEFB composting facilities have been discontinued in POMs including PTPN VII Bekri.

Figure 4: Untilization of EFB: (a) composting of OPEFB-POME using aerated bunker system, (b) composting of OPEFB-POME using windrow system, and (c) as mushroom cultivation media (Photo by author: AH = Agus Haryanto).

Alternative applications for OPEFB include its use as a mushroom growing medium (Figure 4c) and raw material for fuel pellets. The relatively high carbon content and calorific value are some of the reasons for using OPEFB as a raw material for making fuel pellets. Pellets from OPEFB can have a calorific value of 15.8 MJ/kg and can be used as fuel for households and industries. However, the application of OPEFB pellets is limited due to the high ash content (Haryanto *et al*., 2021). In applications involving high temperatures such as boilers, ash will cause problems such as slagging and fouling. Recently, OPEFB was reported as a good material for cultivating rice straw mushrooms that can be developed to improve the economic of the community around a POM (Triyono *et al*., 2019). It, however, involves only little parts of the available OPEFB. Due to the high water content and the presence of oil in the OPEFB, several researchers have studied the potential of using OPEFB as a substrate for producing biogas. The following subsection will summarize the results of studies related to the potential of OPEFB as a biogas substrate.

3.4.2. OPEFB Biogas

The amount of POME is greatly dependent on availability FFB to be processed and is limited during the low crop season due to the lower palm oil production. Researchers are continuously exploring methods to improve biogas production from POME through pretreatment techniques, optimized digestion conditions, and co-digestion with other wastes. Ongoing research aims to improve the understanding of the anaerobic digestion process, leading to more efficient and reliable biogas production. Research focused on developing affordable and scalable biogas production technologies suitable for different settings, including large-scale palm oil mills and small-scale biogas plants.

OPEFB is a material rich in organic matter that can be utilized as a substrate for biogas production through anaerobic digestion with the highest comparative advantage because it is abundantly available and already located in the same environment where POME is produced, thereby saving costs for material provision and transportation. OPEFB is a promising substrate for methane production through solid state anaerobic digestion (SS-AD) process with methane production of 55 m^3/ton, equivalent to yield of 144 mL CH_4/gVS at OPEFB-to-Inoculum ratio of 2 : 1 (Chaikitkaew *et al*., 2015). Research into biogas production from OPEFB is driven by the need for sustainable energy and waste management solutions in the palm oil industry. Converting OPEFB into biogas offers a sustainable solution by transforming waste into a renewable energy source. By utilizing OPEFB for biogas production, the palm oil industry can reduce its consumption on fossil fuels and lower its overall environmental impact. Furthermore, biogas production from OPEFB offers a way to address the environmental impact of palm oil production by reducing the amount of waste sent to landfills or incinerated. Converting OPEFB into biogas provides not only an economic opportunity to add value to a previously discarded waste product, but also reduce the costs associated with waste disposal and treatment, as well as creating new economic opportunities in areas like energy generation, fuel production, and waste management.

Table 7 summarizes results from anaerobic digestion of OPEFB for biogas production. Early research on using EFB as a biogas substrate focused on demonstrating the feasibility and potential of this waste stream for biogas production. Initial papers explored the basic process of anaerobic digestion with EFB, often including physical or biological pretreatment to improve digestion efficiency. Studies also investigated the impact of factors like mixing ratios with other substrates (like Palm Oil Mill Effluent) and the optimal temperature and water content for biogas production.

Table 7. Summary of research results on the anaerobic digestion of OPEFB under different conditions

Conditions	Important Results	References
Lab scale digester of 50-L capacity was used at three conditions: dry fermentation (TS 69.3 and 72.8%); semi-wet fermentation (TS 54.3 and 67.3%); and wet fermentation (TS 42.0 and 49.6). Anaerobic digestion used inoculum seed (cowdung 1 kg diluted in 5 L water).	The optimum biogas production were produced in semiwet fermentation conditions (TS = 67.3%). It was produced 37.462 liters (2.42 L CH4/kg VS) of biogas, but the methane content was considerably low (26.23%).	(Purnomo *et al*., 2018)
Various pretreatment methods was investigated to study their effects of on the anaerobic digestibility of OPEFB for methane production. Six different pretreatment methods were evaluated, including microwave, hydrothermal at temperature (180, 190, and 200 °C), acidified POME, weak acid (2 % acetic acid), weak alkaline (2 % Ca(OH)2), and biogas effluent.	Methane yield from untreated OPEFB was 189.45 mL-CH4/g-VS. All pretreatments improved methane yield with the highest (277.11 mLCH4/g-VS) resulted from pretreatment using weak alkaline, followed by hydrothermal at 180 °C (244.33 mL-CH4/g-VS), and biogas effluent (238.32 mL-CH4/g-VS). The energy and economic analysis, OPEFB pretreatment using weak alkaline showed the highest net energy balance with (8.73 kJ/g-VS) and a short break-even point of 2 years.	(Saelor *et al*., 2024a)
OPEFB and palm oil decanter cake (DC) at 15% TS content were co-digested under solid-state anaerobic (SS-AcoD) at mesophilic conditions 35 °C and thermophilic conditions (55 °C). The digestion used substrate to inoculum (S:I) ratio of 3:1.	The mono-digestion of OPEFB resulted methane yield of 353.0 mL-CH_4/g-VS. Thermophilic mono-digestion with 5% OPA addition resulted methane yield of 365.0 mL-CH_4/g-VS for OPEFB. At OPEFB:DC ratio 1:1 (VS basis), the addition 5% ash, produced CH_4 414.4 (mesophilic) and 399.3 mL (thermophilic) per g VS	(Tepsour *et al*., 2019)
OPEFB was hydrothermally treated and the leachate was anaerobically digested with L/S ratio of 5:1, at 33.5±0.5 °C, for 60 days. The digestion was performed with 10 gTS mixed with 10 gTS of inoculum effluent up to the volume of 500 mL and pH of 7.0 ± 0.2.	HTT treatment resulted in K-removal efficiency of 90.9% and the subsequent methane yield from leachate of 29.1 m^3CH_4/tonEFBdry were achieved. AD of OPEFB also removed K efficiently at 92.6% and produced methane yield of 117.5±1.4 m^3CH_4/tonEFBdry.	(Saritpongteeraka *et al*., 2022)
RSM methodology was employed to optimize methane production from OPEFB pretreated using subcritical water. Impacts of liquid to solid (L/S) ratio (10–20), temperature (120–180 °C), and time (10–30 min) on the CMY (cumulative methane yield) was examined.	Combination treatment of SCW at 120 °C, 10 min, and L/S ratio of 20 increased the CMY to 803.36 mL CH4/gVS, and VS removal of 36.61%. The SCW pretreatment for OPEFB produce more methane yield by 55.42% higher and greater gross energy production (124.30 %) as compared to the untreated OPEFB.	(Hamzah *et al*., 2024)
OPEFB was pretreated by soaking in NaOH at concentrations 0.5 M, 1.25 M, and 2 M by for 60 min at 100 °C. The biogas production of the pre-treated OPEFB was done for 21 days	Pretreatment using 2 M NaOH improved the delignification of 26.465%. The highest biogas production increase by 251.16% as compared to the anaerobic digestion of the untreated substrate.	(Akbar *et al*., 2024)
Anaerobic biogas production from OPEFB was performed at an inoculum to substrate ratio (I/S) of 6:1 for 30 days at 37 °C.	According to the results, the specific methane potential of OPEFB without any pre-treatment was 0.110 m^3/kgVS added. However, the issue with EFOB's high lignin content has prevented the best possible biogas generation.	(Suhartini *et al*., 2020)
Dry OPEFB was shredded to size of 2–5 cm and hydrothermally pretreated at 190 °C (HTP190) for for 5 min. Biogas production under high solid anaerobic digestion (HSAD) was performed to compare mono-digestion and co-digestion of the pretreated OPEFB with decanter cake (DC). HTP190 was co-digested with decanter cake (DC) at at mixing ratios of 5, 10, and 15 %w/v.	The co-digestion of 5%w/v DC produced the greatest methane yield of 372.69 mL CH_4/g-VS, which was 15% more than the mono-digestion of HTP190-EFB (324.30 mL CH4/g-VS) alone. The co-digestion with 5%w/v DC produced the largest synergistic methane output of 77.65 mL CH_4/g-VS. In comparison to mono-digestion, the co-digestion of hydrothermally pretreated OPEFB with DC boosted the yield of biogas by promoting the growth of bacteria contributing to enhanced biogas production.	(Chanthong *et al*., 2024)
OPEFB cuts of 2-5 cm size was pretreated using fungi and was used as biogas substrate at concentration of 0 %, 4 %, 7 %, 10 %, and 100 % w/w (in POME). Batch anaerobic digestion was carried out in batch mode using a 500-mL flask with 30 % w/w seed starter.	The addition of substrate (S) increased CH_4 concentration from 6 % to 60 %. POME 0-S100 had the highest CH_4 production. The absence of POME in the 0-S100 mixture produced better biogas than POME alone and the POME-substrate mixture.	(Ali *et al*., 2024)

According to (Tong & Lee, 2012), OPEFB biogas technology is included in the solid or dry anaerobic digestion type with organic substances between 25% and 40%. Apria (2014) conducted anaerobic digestion of 16 kg of shredded OPEFB for 43 days and produced 1,561.4 L of biogas using seed from cowdung, and 1,235 L using seed from sludge of POME biogas. The CH_4 content, however, was still low, namely 36.1% using cowdung seed and 40.1% using sludge seed. The high lignin content of OPEFB can hinder the digestion process, necessitating pretreatment methods to improve its biodegradability. Co-digestion of OPEFB with other substrates like palm oil mill effluent (POME) can enhance biogas production. A study showed that a mixture of OPEFB and POME at a ratio of 2:1 (w:v), incubated at 37°C for 45 days, produced a high yield of methane (Purnomo *et al*., 2018). Tanimu *et al*. (2025) also reported that OPEFB reached biochemical methane potential (BMP) of of 258 $mLCH_4$/g VS and achieved the impressive degree of methanation (48.3%).

3.5. OPEFB-POME Co-digestion

Co-digestion is the most widely used approach to enhance process stability, equalize macronutrient (C and N) and micronutrient levels, encourage synergistic interactions among microorganisms, and reduce the concentration of inhibitors in anaerobic digestion systems (Choong *et al*., 2018; Hagos *et al*., 2017; Mata-Alvarez *et al*., 2014). Co-digestion able to improve the whole anaerobic digestion performance and the biogas production effectively (Bouallagui *et al*., 2009; Yen & Brune, 2007). Some co-substrates had been reported able to improve both biogas production and methane content through co-digestion with POME, including OPEFB (Kim *et al*., 2013; Saelor *et al*., 2017), combination of microalgae and OPEFB (Ahmad *et al*., 2014a; 2014c; 2015), decanter cake (Hoon *et al*., 2024; Y. F. Lim *et al*., 2021), sewage sludge (Sivasankari *et al*., 2013; Suksong *et al*., 2017), *Moringa oleifera* extract (Yap *et al*., 2021), skim latex serum (Kongjan *et al*., 2018), crude glycerol (Prasertsan *et al*., 2021), and manure (Darwin *et al*., 2021; Sidik *et al*., 2013). Table 8 summarizes results from anaerobic co-digestion of OPEFB with POME for biogas production.All research reported that addition other material as co-substrate improve the anaerobic digestion of POME in term of biogas yield and methane production.

It can be surmised from Table 8 that OPEFB co-digestion with POME improves substrate availability. In addition, OPEFB co-digestion with POME improves substrate biodegradability or removal efficiency. Lastly, OPEFB co-digestion with POME increases biogas and methane production.

3.6. Future Prospect and Challenges

From the previous explanation, it can be concluded that OPEFB has great potential to increase biogas production from POME through anaerobic digestion. The use of biogas can reduce the environmental burden of POMs in terms of reduced water consumption and reduced greenhouse gas emissions (Aziz & Hanafiah, 2020). However, currently, there are at least two important issues that need to be considered regarding OPEFB-POME co-digestion. First, how to conduct co-digestion efficiently and effectively. This is related to the characteristics of OPEFB, which consists of strong and resilient solid fibers. These fibers are not easily decomposed biologically. Akbar *et al*. (2024) asserted that EFB can act as a source of nutrition with POME in the production of biogas by anaerobic digestion. However, EFB's lignin content inhibits biogas production by hindering the access of microbes to the nutrients. The recalcitrance of the OPEFB lignocellulosic structure is a key hindrance to high methane production, even with co-digestion with palm oil mill effluent (Hamzah *et al*., 2024). High lignin content can hinder the digestion process, necessitating pretreatment methods to improve its biodegradability. OPEFB will also float in water. Mixing OPEFB directly with POME will form a solid-liquid mixture that will be ineffective because OPEFB fibers are difficult to degrade. OPEFB fibers will even float and trigger the formation of scum that will inhibit the anaerobic digestion process itself. This co-digestion process will be more effective if carried out in a homogeneous liquid mixture. In this case, only the liquid component of OPEFB is mixed with POME. After being soaked in POME, the OPEFB is then pressed. The resulting juice is used as a co-substrate for the co-digestion process with POME. Amelia *et al*. (2024) reported the co-digestion of OPEFB juice with POME increases biogas and methane production. Compared to POME mono-digestion, the batch co-digestion of POME with OPEFB juice improve biogas production by 54.1% when the OPEFB was manually shreded, and by 45.5% to 75.2% when the OPEFB was mechanically crushed. Under continuous mode with HRT 25 days and similar substrates, the co-digestion was predicted to increase biogas production up to 43.3% using shredded OPEFB and 62.6% using crushed OPEFB. In order to determine the best mixing ratios of OPEFB pressing wastewater, inoculum, and POME, Suksaroj *et al*. (2023) conducted batch experiments at 35 °C. The most effective combination was found to be 45% POME, 50%

Table 8. Research results on biogas yield of OPEFB-POME codigestion under different conditions

Conditions	Important Results	References
OPEFB was crushed into < 5 mm and mix to POME at ratio 0.4:1; 0.8:1; 2.3:1; 6.8:1; 11:1. Anaerobic co-digestion was performed under 4 treatments, namely: (1) untreated OPEFB; (2) OPEFB treated with 1% NaOH (w/w); (3) hydrothermal treatment using steam at 230 °C for 15 min; and (4) combination of hydro-thermal and chemical (0.1% NaOH).	Co-digestion of OPEFB-POME enhanced biodegradability and increased methane production by 25–32% higher at mixing ratios of 0.4:1, 0.8:1 and 2.3:1 on VS basis than digesting only OPEFB. The methane yield was 276–340 mL CH_4/g VS-added for co-digestion of OPEFB-POME at mixing ratios of 0.4:1–2.3:1. The maximum methane produced from co-digestion treated OPEFB-POME was 82.7 m^3 CH_4/ton of mixed treated OPEFB-POME (6.8:1), higher than POME alone of 33.2 m^3 CH_4/ton POME, or OPEFB alone of 79.1 m^3 CH_4/ton EFB. The electricity production of one ton mixture of treated OPEFB-POME is 1190 MJ or 330 kWh.	(O-Thong *et al*., 2012)
Anaerobic co-digestion was performed using intermittent CSTR (working volume 10 L) operated at 35±1 °C. The POME concentration was kept at 4.8 gCOD/L, while OPEFB:POME ratios were 0.12:1.0; 0.25:1.0; 0.31:1.0; 0.62:1.0; 1.0:1.0 (COD basis)	EFB addition to POME improved the specific and total methane production. At EFB:POME ratio 0.25–0.31 achieved specific methane yield rate of 50.8mL CH_4/g VSS.d, which was 1.2 times higher than that of POME alone.	(Kim *et al*., 2013)
POME was mixed with various OPEFB pressed wastewater at ratio 2.5:97.5; 5:95; 10:90 and seed concentration of 35%, 50%, and 75%.	The maximum methane yield of 218 mL CH_4/g VS_r at mixture ratio 0.9:0.1:1 (POME:OPEFB pressed water:seed). The co-digestion improve biogas yield by 96% and CH_4 by 97%, in comparison to digestion POME only.	(Jearat *et al*., 2014)
The EFB was shredded to 1–2 cm. Mixture of POME and the shredded EFB was added gradually to 20 L polyethylene (PE) tank for 14 days. The loading rate was 100 mL POME + EFB (according to treatment ratio, namely 4:96 to 49:51).	The cumulative methane production increased from 0.17 L CH_4 or 0.3668 mL CH_4/g VS (without EFB admixture) to total 2.03 L CH_4 or 0.5932 mL CH_4/g VS (with EFB addition at ratio of 24:76 (10 L of POME, 3.1 kg of EFB). The removal efficiency as compared to control (only POME) was: TVS 78% vs. 57%, BOD 92% vs. 97%, COD 27% vs. 58%.	(Nurliyana *et al*., 2015)
Anaerobic co-digestion of OPEFB with POME was evaluated under mesophilic condition (37 °C). Empty fruit bunches was shredded in size of 0.5, 3.25 and 6 cm. The amount of POME and OPEFB was varied from 2 to 10 gVS with OPEFB:POME ratio 1:1 (based on VS)	Highest biodegradability (63–70%) and methane yield (320 mL/gVS) were achieved at OPEFB size 0.2 mm. The POME:EFB ratio of 4.5–7.5 and EFB size 3.3–6 cm shown acceptable biodegradability value of 40–50% with a methane yield of 282 mL CH_4/gVS. The POME:OPEFB ratio of 4.5–7.5 and size EFB of 3.3–6 cm was more practical for biogas production due to reducing cost. The highest cumulative methane was 2,256 mL CH_4 correspond to 52 m^3 CH_4/ton biomass at ratio 2:6. The highest CH_4 yield was 323 mL/gVS at ratio of 2:2 and EFB size 0.5 cm.	(Saelor *et al*., 2017)
Shredded OPEFB (± 5 cm) was mix with POME at ratio 1:20; 1:25; 1:30; 1:35; 1:40. Batch reactor (working volume 6 L) with seed starter 15% + mixture POME-OPEFB, pH was kept at 7±0.2 by adding $NaHCO_3$. HRT 15 d.	Co-digestion POME and EFB with mixing ratio 35:1 reached the highest gas production of 80.30 L/mg.VS, highest COD reduction of 63.1%, and highest methane content of 80.10%	(Octiva *et al*., 2018)
EFB was grinded, and sieved to get size of 1-3 mm, then pre-treated chemically using NaOH. OPEFB:POME ratio was 0.15:1 and 0.6:1. The experiment was conducted at feed-to-inoculum (F/I) ratio of 0.52 in terms of VS and organic loading of 0.11g VS/L.	Co-digestion of pre-treated OPEFB-POME at ratio 0.15:1 produces 3.67 times, while at ratio of 0.6:1 (equivalent to 29.6 kg EFB/m^3 POME) and thermophilic condition produces 3.36 times more of methane compared to monodigestion of POME. At the optimal EFB-POME ratio 0.6:1 produce the highest methane yield of 74.02 ml CH_4/gVS at thermophilic condition.	(Hong *et al*., 2019)
The co-digestion of POME-OPEFB was performed using Expanded Granular Sludge Bed (EGSB) Reactor operated continuously with 2 days HRT for 48 days under mesophilic (35±2 °C) and thermophilic (55±2 °C). The OPEFB:POME mixing ratios were 0:1; 0.10:1; 0.15:1; and 0.20:1.	The co-digestion of OPEFB-POME at a mesophilic condition and mixing ratios of 0.10:1 resulted the highest COD removal efficiency of 61.97–78.87% and highest biogas production with total volume of 7.40 L (0.1359 – 0.1619 m^3 CH_4/kg CODr) and. Under a thermophilic condition, the same mixing ratios resulted COD removal efficiency of 61.97–74.65% with the highest biogas production of totally 1.35 L (0.0859 – 0.1358 m^3 CH_4/kg CODr).	(Fitrah *et al*., 2019)
The OPEFB was shredded into 1–2 cm length. Co-digestion was performed with 4 Reactor, namely C-NA (Co-digestion non-augmented (POME-EFB); C-B5 (Co-digestion + 5% (v/v) *B. subtilis*; C-B10 (Co-digestion + 10% (v/v) *B. subtilis*; and C-M5 (Co-digestion + 5% (v/v) with mix methanogens.	Bio-augmentation using *B. subtilis* and mix methanogens improve CH4 yield from single-digestion of OPEFB, especially at low bacterial loading. The CH_4 production under 5% bacterial loading was 0.32 L under S-M5 and 0.27 L with S-B5, higher than those of 10% loading, which were 0.14 L (S-M10) and 0.10 L (C-B10). BOD reduction achived 80.5–85.5% and 77.8–78.8% respectively for single and co-digestion samples, significantly lower as compared to those of non-augmented samples with 97.4% and 92.5%. Reduction of COD was for single digestion samples was 86.7% (S-B5) and 87.3% (S-M5), significantly higher than those of co-digestion, namely 63.7% (C-M5) and 61.8% (CM10).	(Chin *et al*., 2020)

Conditions	Important Results	References
OPEFB was ground to particle size of 5mm. Biohythane production was at the substrate to inoculum ratio of 2:1, temperature of 55 °C, HRT 50 days, at 5–20% TS corresponding to initial VS loading of 48–72 g VS/L.	A 2-stage co-digestion OPEFB-POME produce biohythane of 23–30.3 m^3/ton, increased 44.7–90.9% compared to digestion POME alone (15.9 m^3/ton). Single co-digestion enhanced CH_4 yield from 13.2 m^3CH_4/m^3 (POME only) to 48.7 m^3/ton (initial VS 40 g VS/L) to 81.9 m^3/ton (initial VS 10 g VS/L). Codigestion increased hydrolysis constant (kh) of OPEFB from 0.07–0.113 to 0.120–0.223 d^{-1}.	(Mamimin *et al.*, 2019)
Horizontal CSTR, working volume 5 L; temperature 40 ºC; 30 days HRT; seed sludge 30% (v/v). EFB-POME mixture at 33.3 mL/L/at OPEFB:POME 1:2 was fed for 21 d; OLR 6.03 gVS/L/d. Effluent recycling rate varied from 0 (zero) to 22.2 mL/L/d.	Recycling rate R2 (16.7 mL/L/d) resulted the highest VS removal efficiency (30.8%) and methane yield of 135 mL-CH_4/g VS. Other recycling rates produced lower methane yields of 123, 60, 121, and 102 mL-CH_4/g VS for respectively R1, R3, R4, and (R5).	(Suksong *et al.*, 2020)
Anaerobic co-digestion was performed with 1800 ml seed sludge at 39 °C. Two different OPEFB:POME ratios were investigated, namely 1:4 (w/v) with 40 g OPEFB and 160 mL POME, as well as 2:3 (80 g OPEFB and 120 mL POME).	The optimum pH was between 6.8 - 7.2. Biogas production 40,200 mL at ratio 1:4, and 39,500 mL at ratio 2:3. The degradation percentage in term of BOD, COD, TS, and VS removal was respectively 81.3; 87.9; 52.0; and 46.2 for ratio 1:4, and 74.7; 72.9; 40.9; and 56% for ratio 2:3.	(Kamal *et al.*, 2021)
Two CSTR reactors with capacity of 1 m^3 of POME were arranged horizontally, with the end containing the tap. The biodigesters were operated at temperature of 30–40 °C, with HRT of 28 days. OPEFB:POME ratio varied from 4:96 to 49:51	Co-digestion OPEFB-POME improved the specific rate and the ultimate methane production by 29.6%. Alkaline pre-treated OPEFB produced more biogas (94%) with CH_4 content increased up to 66%. The biogas yield from POME-OPEFB ranges from 62 to 83 m^3/m^3-POME with maximum value of 128 m^3/h (enhancement by 30%) in comparison with the mono-digestion of POME alone.	(Park, 2021)
Anaerobic co-digestion was performed at F/I ratio 0.52 (VS basis) and OLR of 0.31 g VS/L/day under mesophilic (35 °C) and thermophilic (55 °C), with and without NaOH pretreat-ment. The OPEFB:POME ratio was 0.3:1 to 0.75:1 for NaOH pretreated OPEFB, and 0.15:1 to 0.45:1 for no pretreatment	The highest gas yield for both pretreated and untreated OPEFB occurred at OPEFB:POME ratio of 0.6:1. Methane production for NaOH pretreated was ~640 mL CH_4 in mesophilic, and ~810 mL CH_4 under thermophilic temperatures. For untreated OPEFB, the methane production was ~360 mL CH_4 in mesophilic, and ~525 mL CH_4 under thermophilic conditions. Anaerobic co-digestion performed 2.36 times better than mono-digestion of POME at mesophilic conditions.	(Liew *et al.*, 2021)
Anaerobic digestion using raw and spent mushroom OPEFB under semi-continuous solid-state conditions using 1.5 L reactors (1.0 L working volume) with seed sludge of 70% (w/v) and substrate to inoculum (F:I) ratio of 2:1. Mono-digestion of raw OPEFB used TS of 15%, while for spent mushroom used 15% to 30% (5% incremental). For spent mushroom co-digestion used ratio of spent mushroom OPEFB:POME were 1:4; 1:2; 3:4; 1:1 (based on TS).	Spent mushroom (S-m) OPEFB biodegradability was 62.7%, almost two fold of that raw OPEFB (33.5%). Methane produced from mono-digestion of spent mushroom OPEFB (15% TS) was 50.6±0.9 m^3/t, higher than that of raw OPEFB (42±1.0 m^3/t). The highest methane production from mono-digetion of S-mOPEFB was 50.6 m^3/t, equivalent to yield of 281 mL CH_4/g VS. The co-digestion of S-mOPEFB with 5% POME resulted biodegradability of 90.8% and highest methane yield of 405 mL CH_4/g VS. Increased SM-OPEFB portion decreased biogas yield from 73.3 m^3/t (ratio 1:4); 72 m^3/t (ratio 1:2); 65.3 m^3/t (ratio 3:4) and 55.3 m^3/t.	(Mamimin *et al.*, 2021)
OPEFB and decanter cake (DC) were used separately as co-substrates for POME to increase biogas production. The co-digestion was evaluated at co-substrate to POME ratio 0.15:1; 0.30:1; 0.45:1; 0.60:1; and 0.75:1 (in term of VS).	Anaerobic co-digestion of DC and POME is promising with removal efficiency of > 95% for COD, > 74% for TS, > 90% for VS, > 90% for TSS, and > 92% for VSS. OPEFB is better co-substrate for POME than decanter cake (DC). Co-digestion with POME produce higher methane yield as compared to mono-digestion of POME. OPEFB:POME ratio of 0.6:1 (≈29.6 kg EFB/m^3 POME) improve biogas production by 2.36 times higher than that of mono-digestion of POME.	(Chan *et al.*, 2021)
OPEFB was cut into 2-3 cm long, dried, and ground into 1-2 mm. *Thermoanaerobacterium thermosaccharolyticum* PSU-2 culture was used as inoculum for augmenting process. Anaerobic digestion was performed using bottles with working volume 500 mL and substrate-toinoculum (S:I) ratios of 15:1, 10:1, 5:1, 4:1, 3:1, 2:1, and 1:1.	The augmented *T. thermosaccharolyticum* PSU-2 improved substrate removal efficiency, biogas yield, and methane content. Augmented mono-digestion OPEFB with S:I ratio of 15:1 improved 64.31±1.17% with methane yield 35.13 ± 1.05 m^3/tonne. Augmented co-digestion of OPEFB-POME at S:I ratio of 15:1 further increased methane yield to 46.67 ± 1.40 m^3 CH_4/tonne, or improvement of 103.00 ± 2.81%. Augmented co-digestion OPEFB-POME using *T. thermosaccharolyticum* PSU-2 pretreatment is a promising, energy-efficient, and profitable approach for enhancing biogas from OPEFB-POME.	(Saelor *et al.*, 2024b)
Anaerobic co-digestion was performed using 1-L bottles (worjing volume 100 mL) filled with OPEFB pressed water and POME at ratios (2.5; 5.0; 10%) with seed sludge (20; 35; 50; 75%). The digestion run at temperature 35 °C for 25 days with substrate pH kept at 7 to 7.2.	The highest biomethane potential of 0.016 L CH_4/g VS added or 0.216±0.003 L CH_4/g VSr was resulted from substrate composition of POME + 50% seed + 5% OPEFB wastewater, significantly higher than 50% POME + 50% seed which was only 0.0078±0.001 L CH_4/g VS added or 0.093±0.013 L CH_4/g VSr. The COD removal was 67% for this substrate composition with total biogas production 67,558 mL for HRT 25 days, equivalent to total methane yield of 28,470 mL.	(Suksaroj *et al.*, 2023)
The co-digestion of OPEFB-POME was performed using two types OPEFB (shredded and crushed). The OPEFB was soaked in POME at ratio of 5%, 10% and 15% for 1 to 3 days, and then pressed. The	The co-digestion of OPEFB-POME increases production of biogas and methane. Compared to POME only, batch mode co-digestion of POME with OPEFB (shredded 10%, shredded 15%, crushed 10%, and crushed 15%) improve biogas production by 54.1%, 54.1%, 45.5%, and 75.2%, respectively. For	(Amelia *et al.*, 2024)

Conditions	Important Results	References
liquid phase was anaerobically digested using 2-L digester (working volume 1 L) for 25 days HRT. Each digester was filled with 20% substrate mixture and 80% seed sludge.	continuous mode with HRT 25 days and similar feedstock, biogas production was predicted to increase by 43.3%, 41.6%, 35.6%, and 62.6%, respectively, with methane content maintained at around 60%.	
OPEFB was treated using NaOH solution of 0.1% and then heated hydrothermally at 150, 180 and 200 °C. The anaerobic co-digestion of POME and treated OPEFB was performed under mesophilic conditions (27-30 °C) for 21 days.	Hydrothermal at 180 °C using 0.1% NaOH solution was the best pretreatment for OPEFB. The treatment decrease the lignin of OPEFB by 33.95% and improve biogas production of 202.32%, as compared to that of POME mono-digestion.	(Sanova et al., 2024)
The biogas production from anaerobic digestion of OPEFB was performed under thermophilic and high solid (HS-AD) condition. The effects of particle size reduction (0.5, 3.25, and 6 cm), TS loading (5–40 %), and co-digestion with POME (10–30 % VS basis) were investigated.	At TS loading 15–20 %, the HS-AD OPEFB resulted biodegradability of 24.6–25.1% and produced methane yield of 103.4–105.3 mL CH_4/g VS. At this TS loading, small particle size (0.5 cm) resulted higher hydrolysis rates (45 %) and methane production as compared to that of 6 cm OPEFB. Co-digestion of OPEFB-POME at ratio 1:31 improved degradation of VFAs by a 22.8–38.1 %, and produced 17.77 mL CH_4/g VS, increasing methane yield by 24–46.5 %. The optimized process reached biodegradability of 61.2 % at thermophilic with highest yield of 287.77 mL CH_4/g-VS.	(Saelor *et al*., 2025)
Anaerobic digestion of mixture OPEFB-POME was done with and without microalgae (*Tetraselmis suecica*) co-cultivation. Anaerobic digestion was conducted using aerobic-anaerobic respirator system. Bottles were occupied with 50 mL POME, 150 mL POME sludge, 6 g dry OPEFB, and 100 mL microalgae. The initial pH was kept at 7.8 - 8. The anaerobic digestion was done with HRT 3 and 7 days.	The highest daily biogas and methane yield of 0.1162 m^3/kg COD and 3900.8 mL CH_4/L POME was resulted with microalgae. Without microalgae co-cultivation, daily biogas yield was higher (0.1269 m^3/kg COD), but daily methane yield (3641.8 mL CH_4/L POME) was lower. Anaerobic treatment with microalgae co-cultivation improved biodegradation with removal efficiencies of 95% (COD), 95% (BOD), 90% (TOC, total organic carbon) and 80% (TN, total nitrogen), higher than removal efficiencies of those without microalgae, namely 87% (COD), 87% (BOD), 72% (TOC) and 78% (TN).	(Ahmad *et al*., 2014a)
OPEFB was crushed to get sizes of <4 mm. Microalgae *Nannochloropsis oculata* was co-cultivated during OPEFB treatment. Anaerobic digestion was conducted using 500 ml serum bottles for 3 and 7 days HRT. The experiment was optimized using response surface methodology (RSM). Bottles were filled with 50 mL POME, POME sludge (0 and 150 mL), dry OPEFB (0, 3, and 6) g, and microalgae (0, 50, and 100 mL). The pH was maintained at 7.4–7.5.	Using RSM, microalgae (100 mL) co-cultivation achieved the maximum daily biogas yield of 0.126 m^3/kg COD with biomethane yield of 4813.0 mL CH_4/L POME, which was higher than that of without microalgae with daily biogas and methane of 0.127 m^3/kg COD and 3641.8 mL CH_4/L POME. At lower microalgae (50 mL), the daily biogas yield decreased to 0.121 m^3/kg COD with methane yield 4024.4 mL CH_4/L POME. Anaerobic treatment with *N. oculata* co-cultivation improved biodegradation with removal efficiencies of 95% (COD), 95% (BOD), 90% (TOC, total organic carbon) and 80% (TN, total nitrogen), higher than those of without microalgae with removal efficiencies of 87% (COD), 87% (BOD), 72% (TOC) and 78% (TN).	(Ahmad *et al*., 2014b)
Aerobic and anaerobic experiments were run using 500 mL bottles for 3 and 7 d with initial pH 7.8–8. Bottles were filled with 50 mL POME, 150 mL sludge, 6 g OPEFB and 100 mL *Chlorella sp*., stirred at 200 rpm, 25°C. For anaerobic experiment, bottles were filled with 50 mL POME, sludge (0 and 150 mL), OPEFB (0, 3, and 6) g, and *Chlorella sp*. (0, 50, and 100 mL). The vessels were kept at 48°C, stirred at 300 rpm and pH kept at 7.3–7.5.	Using RSM, the highest daily biogas yield of 0.128–0.129 m^3/kgCOD was achieved with daily methane yield of 5256.8–5295.8 mL/L POME with 50 mL *Chlorella sp*. and 6 g OPEFB. The methane yield was 1.4 fold higher as compared to that of without both microalgae and OPEFB. Anaerobic treatment with *Chlorella sp*. co-cultivation for 7 days improved biodegradation with removal efficiencies of 98% (COD), 95% (BOD), 78% (TOC, total organic carbon) and 78% (TN, total nitrogen), higher than those of without microalgae with removal efficiencies of 96% (COD), 86% (BOD), 68% (TOC) and 64% (TN).	(Ahmad *et al*., 2014c)
Aerobic and anaerobic experiments were run using 500 mL bottles for 3 and 7 d with initial pH 7.8–8. Bottles were filled with 50 mL POME, 150 mL sludge, 6 g OPEFB and 100 mL algae, stirred at 200 rpm, 25°C. Anaerobic experiment: microalgae were inoculated into mixture (fresh POME + OPEFB + seed sludge). The bottles were purged with N_2 gas, and capped with rubber septum and then kept at 48°C and stirred at 300 rpm.	The addition of microalgae improve COD removal efficiency from 58–60.8% (without algae) to (90–97%), and increase biomethane yield by 1.3-fold higher. Co-digestion OPEFB-POME with co-cultivation of *Nannochloropsis oculata* resulted the highest daily specific biogas production of (1.13–1.14 m^3/kg COD) and daily methane yield of (4606–5018 mL CH_4/L POME).	(Ahmad *et al*., 2015)
OPEFB was crushed to get sizes of <4 mm. Microalgae involved *Chlorella sp*. (fresh water strain) and *Nannochloropsis oculata* and *Tetraselmis suecica* as marine strains. Anaerobic digestion was conducted using 500 ml serum bottles. Bottles were filled with 50 mL POME, 150 mL sludge, OPEFB (0; 3; and 6 g), and microalgae at (0; 50, and 100 mL). The pH of samples was maintained to 7.5.	With the presence of microalgae, the highest removal efficiency were achieved at 7 day with COD_r (95-98%), BOD_r (90-98%), TOC_r (81-86%), and total nitrogen (TN) (78-80%). Co-cultivation *N. oculata* and *Chlorella sp*. (both at 50 mL) with OPEFB (6 g) resulted the highest daily methane yield (4,651.9 mL CH_4/L POME) and daily biogas yield (0.124 m^3/kg COD). The combination of *N. oculata* (100 mL) with *T. suecica* or *Chlorella sp*. (each at 50 mL), and OPEFB (6 g) obtained high daily methane yield (4,018.9 mL CH_4/L), but lower daily biogas yield (0.097 m^3/kg COD).	(Ahmad *et al*., 2016) GABUNG

seed, and 5% OPEFB pressing wastewater. This formulation was subsequently applied in semicontinuous fermentation, with an optimal hydraulic retention time (HRT) of 25 days. Under these conditions, the cumulative biogas yield reached 18,679 mL/L, including 6,778 mL/L of methane. The methane fraction was 62%, while the chemical oxygen demand (COD) removal efficiency achieved 67%.

A practical application of this concept in the field can be achieved by providing a separate pond for soaking the OPEFB with POME. The hot fresh POME (approximately 70–90°C) has several advantages including accelerating the release of organic compounds from the EFB to the liquid, increasing material transfer efficiency, and utilizing waste heat at no additional cost. The OPEFB is then pressed, and the resulting liquid is fed into the biogas-POME facility (Figure 5). This method increases the COD value of the substrate, which in turn increases biogas production.

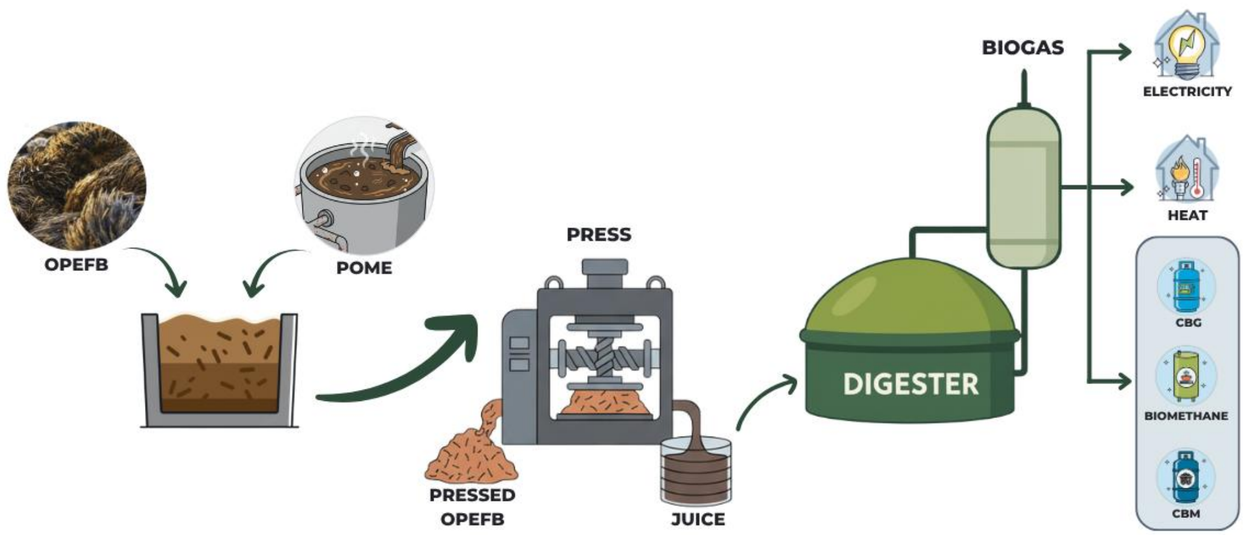

Figure 5. Proposed concept for improving biogas using OPEFB-POME anaerobic co-digestion

The second challenge relates to the utilization of biogas itself. Biogas can be used as fuel for electricity generation or as steam for palm oil mills. However, on-site biogas use in palm oil mills is very limited, given that energy needs are already met by generators that use solid fuels, namely mesocarp fiber and shells. So, the majority POMs are already self-sufficient in energy, primarily utilizing solid wastes from the palm oil production process as fuel for steam and electricity generation (Erivianto & Dani, 2024). Biogas from POME in Indonesia remains underexploited, with less than 10% of mills having biogas plants and only a small share contributing electricity to the grid. Expanding its use requires stronger policies, infrastructure, financing, and innovation to transform POME biogas into a major clean energy source for the palm oil sector. In some cases, palm oil mills can even generate a surplus of energy from burning their solid wastes, which can potentially be used to power local communities or sold to external parties. This practice indeed helps reduce reliance on external energy sources and lowers GHG emissions. For example, a mill using biomass as fuel can reduce emissions by 456.83 kg CO_2e per ton CPO compared to a mill relying on fossil fuels (Hong, 2023). Second, most of the new PKS are located in remote areas (Mohtar *et al*., 2017). This makes it difficult to distribute biogas as fuel such as LPG to the community. If biogas is converted into electricity, the distribution of electricity generated to electricity users is also constrained by the absence of electricity network facilities.

Off-site electricity generation using biogas is also difficult because fuel oil refineries are generally located far from residential areas and lack electricity network from the state electricity company (PLN). Mostly, biogas is captured for energy production, but POMs are generally self-sufficient in energy from the use of solid waste (shells and mesocarp fiber) (Tong & Lee, 2012). For example in Malaysia, out of the 92 plants, 14% was co-fire the biogas in the biomass boilers, 28% for generating electricity, 56% just flaring the biogas, and 2% use the biogas for thermal energy (steam) production (Loh *et al*., 2017a). Similar situation also found in Indonesia. Indonesia currently has over 800 palm oil mills, but only about 10% have installed biogas plants. Among those with biogas facilities, just 2% operate as

Independent Power Producers (IPPs) selling electricity. Around 43% sell excess electricity generated, while 55% use the electricity mainly for captive power or flaring (Sukardi & Brata, 2021). However, captive power consumption is typically minimal since palm oil mills generally sustain themselves using biomass power plants. This means only a small proportion of biogas is effectively utilized, with less than half being converted to electricity and fed into the grid. In addition, high capital costs for construction, limited funding, lack of incentive policies, and limited technical capacity are obstacles in implementing POME-based biogas systems (Tantitham *et al*., 2009).

Table 9. Characteristic of CBG, Biomethane, and Bio-CNG

Feature	CBG	Biomethane	Bio-CNG
Methane %	50–70%	>96%	>95–97%
CO_2 content	High	Very low	Very low
H_2S, moisture	Present	Removed	Removed
Compression	Yes	Optional	Yes (to ~200–250 bar)
Usage	Electricity, heating	Grid injection, vehicles	Vehicle fuel
Purification	Low to medium	High	Very high
Similar to	Raw biogas	Natural gas	Compressed natural gas (CNG)

Therefore, it is necessary to consider more effective and efficient ways to utilize biogas. One idea worth to consider is improving the quality of biogas to make it into a compressed biomethane gas fuel, equivalent to compressed natural gas (CNG) that can be blended into the gas networks or used as a transport fuel. This can be achieved by upgrading biogas quality by removing the unwanted gaseous components to achieve a quality comparable to that of CNG. In this case the biogas purification process must achieve the following qualities: CH_4 content (>97%), CO_2 (<3%), H_2S (<10 ppm), and water content (<32 mg/Nm^3) (Tong & Jaafar, 2006). Upgrading biogas to biomethane could be a major source of future growth (IEA, 2020).

The terms of compressed biogas (CBG), biomethane, and bio-CNG are closely related but differ slightly in gas composition, purity level, and application. Table 9 summarizes their key differences. CBG is biogas that has been compressed for storage and transport, usually under high pressure (like 200–250 bar). The gas composition typically contains 50–70% methane (CH_4), 30–50% carbon dioxide (CO_2), and Traces of hydrogen sulfide (H_2S), moisture, and other impurities. The gas can be used for heating or electricity generation, but not ideal for vehicle fuel unless purified. Biomethane is purified biogas (Amin *et al*., 2022) similar to natural gas in composition and energy content. Biomethane has a high methane content (typically >96% CH_4) achieving by removing CO_2, H_2S, water vapor, and other impurities. Biomethane can be injected into the natural gas grid or used as vehicle fuel after compression. With high purification level, biomethane can be stored as compressed (Bio-CNG) or liquefied (Bio-LNG) and is suitable for most applications, including vehicle use. Bio-CNG (Compressed Natural Gas from Biomethane), also called green CNG, is biomethane that is compressed (usually to 200–250 bar), making it suitable as an alternative vehicle fuel. It is functionally equivalent to Fossil-based CNG, but renewable. With very high purification level to meet vehicle-grade standards (like >95–97% methane), bio-CNG can be utilized to directly replace CNG in cars, buses, and trucks. In shorth, CBG is raw biogas compressed, still contains CO_2 and impurities; Biomethane is cleaned-up biogas, pure methane, but may not yet be compressed; and Bio-CNG is compressed biomethane that is ready for vehicle fuel.

Nasrin *et al*. (2020) reported that combination of biological and physical purification techniques effectively removed approximately 99% hydrogen sulphide (H_2S) and 88% of CO_2. The resulting Bio-CNG contained about 92% methane (CH_4), 7% CO_2, and 0.9% oxygen (O_2), with H_2S reduced to trace levels of 5 ppm. The purification process increased the biogas calorific value from 20.0 MJ/m³ to 35.0 MJ/m³. Compared to a conventional biogas plant, the Bio-CNG plant indicated an internal rate of return of around 14% and a payback period of approximately 6 years for a mill with FFB capacity 60 t/h thereby technically and economically viable. Biogas pretreated using chelate-iron (EDTA-iron solution) can remove hydrogen sulfide (H_2S) up to 99%. A pilot-scale purification plant for upgrading biogas to CNG with a capacity of 30 m^3/h resulted gas composition of 98% CH_4, 2% CO_2, 0.004% H_2O, and 1 ppm H_2S (Park, 2021). Meanwhile, Febijanto *et al*. (2024) concluded that to achieve an IRR 12%, the bio-CNG produced from a covered lagoon biogas digester of a POM with capacity 60 t/h must be sold at a price of at least 10.7 USD/MMBTU.

4. CONCLUSION

The review confirms that biogas production from POME through anaerobic digestion has evolved into a mature and proven technology, capable of supporting Indonesia's renewable energy and carbon reduction targets. The historical progression from open ponding systems to covered lagoons and high-rate reactors reflects significant improvement in energy recovery efficiency and environmental performance. However, the conventional mono-digestion of POME still faces limitations related to process instability, seasonal variation in substrate availability, and low nutrient balance. Co-digestion with OPEFB offers a strategic alternative by enhancing microbial activity, improving C/N balance, and increasing methane yield while simultaneously reducing two major waste streams of the palm oil industry. Various studies demonstrate that POME–OPEFB co-digestion can achieve higher biogas yield and better digestate quality suitable for biofertilizer use. This integration not only supports the zero-waste vision but also promotes circular bioeconomy within palm oil agro-industry. Nevertheless, large-scale adoption requires addressing several technical and institutional barriers, including the need for efficient OPEFB pretreatment, reliable feedstock logistics, and financial incentives for renewable energy generation. Future research should focus on optimizing co-digestion ratios, applying advanced microbial consortia, and developing energy-efficient biogas upgrading technologies such as biomethane and bio-CNG. Strengthening policy frameworks and industry collaboration will be crucial to scale up this sustainable waste-to-energy model and to achieve the goal of a low-carbon, zero-waste palm oil industry.

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