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RENEWABLE ENERGY AND GREENHOUSE GASES EMISSION REDUCTION POTENTIAL OF BIOGAS FROM PALM OIL MILL EFFLUENT

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ABSTRACT

Emissions of biogas from palm oil mill effluent (POME) via anaerobic digestion is a greenhouse gas (GHG) that can be mitigated by capturing and utilising as renewable energy (RE). Huge energy potential of biogas has been reported, but none has specifically explored this potential based on actual scenario of mills equipped with biogas plant in the Malaysian palm oil industry. This study analyses the potential of biogas from POME for RE and GHG emissions reduction from two scenarios: overall (nationwide) and mills having biogas plant. The overall potential of biogas volume, electricity generation and bio-compressed natural gas (Bio-CNG) production from all palm oil mills in 2021 were estimated at 1648 million m^3, 508 MW and 988 million m^3 Bio-CNG, respectively. With 135 mills having biogas capturing facilities, 33% of the country's overall potential energy from POME could be harnessed and utilised, to potentially mitigate 4.96 million tonnes CO_2eq GHG annually. The study indicated that electricity generation is the major use of biogas in the country, particularly for grid connection. Activities of biogas capture and utilisation have thus demonstrated a feasible approach in addressing sustainable issue of the palm oil industry, which contribute to RE and GHG reduction targets in Malaysia.

Keywords: bio-compressed natural gas, biogas utilisation, electricity, palm oil, sustainability.

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INTRODUCTION

Fossil fuels such as crude oil, natural gas and coal contributed about 93% to the primary energy supply in Malaysia in 2018 (Suruhanjaya Tenaga, 2021). Heavy dependence on fossil fuel may lead to energy crisis as well as an increased environmental problem such as global warming. Over the past years, two detrimental global threats, *i.e.*, COVID-19 pandemic and Russia-Ukraine crisis had seriously attributed to energy crisis with positive impact on greenhouse gases (GHG) emission. This unprecedented phenomenon serves as a catalyst for boosting the world to transition from fossil fuels to renewable energy (RE) while focusing on economic recovery measures. RE has been placed as a long-term solution for cushioning energy security and climate change in line with the Sustainable Development Goals 7 and 13 established by the United Nations in 2015 (United Nations, 2022). Under the Malaysia Renewable Energy Roadmap 2035, the Government targets to increase RE share in the national power installed capacity to 31% by 2025 with foreseeable reduction in GHG emissions (SEDA, 2022). Biomass including biogas generated from the palm oil industry could play a vital role in supporting the country's RE development and GHG mitigation targets.

Malaysia is the world's second largest producer and exporter of palm oil, producing 19.14 million tonnes of crude palm oil (CPO) which contributed

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34.3% to the total palm oil traded worldwide in 2020 (Parveez *et al.*, 2021). As a result, an abundance of non-oil biomass by-products is also generated, including approximately 100 million tonnes (wet basis) of oil palm biomass annually in solid and liquid forms from palm oil mills (POMs) alone. These resources have been commercially used as fuel while many opportunities still exist for RE, in particular biogas from palm oil mill effluent (POME).

POME is the liquid by-product generated from palm oil milling activities, at an estimated volume of >60 million m^3 annually in Malaysia (Loh *et al.*, 2022). It is characterised as a highly polluted wastewater with high value of biological oxygen demand (25 000 mg L^{-1}) and chemical oxygen demand (COD) (51 000 mg L^{-1}) (Bello and Raman, 2017). The conventionally deployed open ponding systems or tanks via anaerobic digestion (AD) for POME is less environmental-friendly with release of biogas to the atmosphere (Loh *et al.*, 2013). Uncaptured biogas consists of mainly 60%-70% methane (CH_4) and 30%-40% carbon dioxide (CO_2), in which both are GHG that cause global warming and major threat to sustainable palm oil production. Biogas capture and utilisation appears to be a promising way to address these issues and add value to POME treatment.

Economic and environmental benefits and potential of biogas from POME in the Malaysian palm oil industry are widely available in the literature. Few studies indicated that POMs equipped with biogas plant generate lower GHG of 134-196 kg CO_2eq t^{-1} CPO, compared to 814-896 kg CO_2eq t^{-1} CPO from conventional mill (Lim and Biswas, 2019; Subramaniam *et al.*, 2010). Lim and Biswas (2019) also reported that an increase of 2.3% annual mill revenue could be achieved by selling the raw biogas to nearby factory. A life cycle cost benefits analysis indicated that energy generation from POME-based biogas using digester tank technology has higher life cycle cost and cost benefits compared to that via covered lagoon technology (Sharvini *et al.*, 2022). In this regard, it is highly potential to encourage more biogas capturing and utilisation activities through policy intervention. Chia *et al.* (2020) reported that 510 000 t of CH_4 were generated from 58.5 million tonnes of POME in 2018. Recently, a computed potential of 3.5 million MWhr of electricity could be anticipated from 1789 million m^3 of biogas in POMs nationwide (Loh *et al.*, 2022). These reported potentials vary significantly as the feedstock availability was only estimated based on the total fresh fruit bunches (FFB) processed nationwide plus standard biomass (feedstock) to FFB extraction rate, regardless of biogas plant status in POMs. To date, biogas actual potential (RE and GHG savings) can only be gauged based on limited assessment, which is theoretical at large, without determining from actual scenario of POMs installed with biogas plants. As current scenario of the industry focuses on sustainable development and income maximisation, an up-to-date biogas status from POME, its roles and contribution for RE and GHG mitigations need to be reviewed and reassessed.

In this study, a systematic reassessment was performed on the RE and GHG savings potential of biogas capture and utilisation in the Malaysian POMs. A series of formulas was constructed and used to determine these potentials based on the latest total number of biogas plant operated in POMs. A survey was carried out to consolidate the status of national biogas development by millers focusing on technology used and utilisation pathway deployed. This study is original and novel in reciting the biogas potentials based on systematic analysis of actual annual FFB processed sourced from the respective mills plus national distribution in biogas pathway including a further breakdown in electricity end-uses and their installed capacity. This kind of information will be the first of its kind in the country that serves to reflect actual progress on the ground. The resulted up-to-date information on biogas development, potential RE plus the associated GHG emissions and potential savings will strengthen national reporting and shed light on future biogas endeavours and improvements gearing towards sustainable palm oil production.

MATERIALS AND METHODS

Potential Biogas and Renewable Energy from Palm Oil Mill Effluent (POME)

Potential of biogas and RE generation from POME was assessed based on two different scenarios, namely overall technical potential and actual potential. The former refers to the country's total potential of biogas calculated from all POMs while the latter analyses the actual potential of biogas generated from the total number of mills installed with biogas capture facilities. The overall technical potential for production year of 2019-2021 was determined based on the actual FFB processed annually (*Table 1*). Amount of FFB processed by 135 mills equipped with biogas plant in 2021 was used to estimate the actual potential of biogas and RE from the respective mills.

Table 1 summarises the primary data used for this study. FFB processing capacity and total amount of FFB processed of the mills from 2019-2021 were sourced from the Economic Industry Development Division, Malaysian Palm Oil Board (MPOB) (MPOB, 2022).

The amount of biogas generated and its potential for various applications such as electricity and bio-compressed natural gas (Bio-CNG) or biomethane could be calculated based on the availability of POME. It is estimated that 1 t of FFB could produce

TABLE 1. APPROVED FRESH FRUIT BUNCHES (FFB) CAPACITY AND AMOUNT OF FFB PROCESSED OF THE MALAYSIAN PALM OIL MILLS (2019-2021)

Year	2019	2020	2021	Mills with biogas plant (2021)
No. of mills	452	457	451	135
Approved FFB capacity, million tonnes	112.91	116.81	116.72	40.10
FFB processed, million tonnes	98.28	96.09	90.53	29.93
[a]Capacity utilisation, %	87.0	82.3	77.6	74.6

Note: [a]FFB processed/approved FFB capacity.

0.65 m^3 POME (Akhbari *et al.*, 2020) with biogas generation rate of 28 m^3 biogas for every m^3 POME (Loh *et al.*, 2017). Equations (1) and (2) as reported in Sarwani *et al.* (2019) were used to calculate the potential amount of $POME_{volume}$ (m^3) and $Biogas_{volume}$ (m^3) from the FFB processed in POMs.

$$POME_{volume} = 0.65 \times FFB_{processed} \quad (1)$$

where 0.65 is the generation rate of POME per t FFB processed (m^3 t^{-1}) (Akhbari *et al.*, 2020) and $FFB_{processed}$ is the amount of FFB processed by the mills (t).

$$Biogas_{volume} = 28 \times POME_{volume} \quad (2)$$

where 28 is the production rate of biogas, m^3 m^{-3} POME (Loh *et al.*, 2017).

The potential of heat energy from biogas: $Energy_{potential}$ (MJ) and $Electricity_{potential}$ (MW), *i.e.*, electricity installed capacity were calculated based on Equations (3) and (4) (Loh *et al.*, 2017) as follows:

$$Energy_{potential} = Biogas_{volume} \times CV_{biogas} \quad (3)$$

$$Electricity_{potential} = Biogas_{volume} \times CV_{biogas} \times \frac{1}{3600} \times \eta_{gas\ engine} \times \frac{1}{7200} \quad (4)$$

where CV_{biogas} is the calorific value of biogas, 20 MJ m^{-3} (Loh *et al.*, 2017), $\frac{1}{3600}$ refers to conversion factor of 1 MJ to MWhr, $\frac{1}{7200}$ is the annual average operation hour (hr^{-1}) of biogas power plant, and $\eta_{gas\ engine}$ refers to 40% efficiency of the gas engine (Chin *et al.*, 2013).

The equivalent potential of diesel and natural gas from the potential energy available from biogas could be determined based on calorific values of diesel and natural gas, which are 35.14 MJ L^{-1} (Chin *et al.*, 2013) and 35 MJ m^{-3} estimated from Lee *et al.* (2019), respectively using Equations (5) and (6) which were developed according to Chin *et al.* (2013):

$$Diesel_{equivalent} = Energy_{potential} \div CV_{diesel} \quad (5)$$

$$Natural\ gas_{equivalent} = Energy_{potential} \div CV_{natural\ gas} \quad (6)$$

Assuming the mean composition of CH_4 in biogas is 60% (Loh *et al.*, 2017), the potential conversion of biogas into Bio-CNG, $BioCNG_{potential}$ (m^3) could be determined using Equation (7) (Sarwani *et al.*, 2019) as follows:

$$BioCNG_{potential} = 0.6 \times Biogas_{volume} \quad (7)$$

where 0.6 is the average ratio of CH_4 to biogas. Since the energy content of natural gas is measured in MMBTu, the equivalent conversion factor used is 1 MMBTu = 28.26 m^3 Bio-CNG (Mundi, 2021).

Greenhouse Gases Emissions and Potential Savings from Biogas Capture and Utillisation

The amount of GHG emissions from biogas of POME could be determined from the amount of CH_4 generated, $CH_{4volume}$ as shown in Equation (8) (Hasanudin and Haryanto, 2018), which is estimated using default value of CH_{4yield}, 0.25 kg CH_4 kg^{-1} COD removed (Chin *et al.*, 2013) as follows:

$$CH_{4volume} = POME_{volume} \times COD_{POME} \times 1000\ (L) \times CH_{4yield} \quad (8)$$

where $CH_{4volume}$ is the amount of CH_4 generated (t) from POME via AD, volume conversion (m^3 to L) of 1000 and COD_{POME} is the mean value of COD for POME, 51 000 mg L^{-1} (Bello and Raman, 2017).

As the global warming potential of CH_4, GWP_{CH_4} is 25 times that of CO_2 (Subramaniam *et al.*, 2021), the associated GHG emissions could be determined using Equation (9) (Loh *et al.*, 2017) as follows:

$$GHG_{emissions} = CH_{4volume} \times GWP_{CH_4} \quad (9)$$

where $GHG_{emissions}$ is the amount of GHG emitted from AD of POME (t CO_2eq), and GWP_{CH_4} is 25.

The potential of GHG savings, $GHG_{savings}$ (t CO_2eq) from biogas capture activities in POMs could be calculated using Equation 10 (Subramaniam *et al.*, 2021) based on an overall 80% of plant efficiency (assumed based on COD removal from POME during AD and also biogas capturing efficiency) as follows:

$$GHG_{savings} = GHG_{emissions} \times 0.8 \quad (10)$$

The potential GHG savings, ($GHG_{electricity}$, t CO_2eq) made from the use of biogas for electricity generation could be determined using Equation (11) according to Subramaniam *et al.* (2021). It was calculated based on an average emission factor (EF) of grid electricity system for Peninsular Malaysia, Sabah and Wilayah Persekutuan Labuan, and Sarawak.

$$GHG_{electricity} = Electricity_{potential} \times 7200 \times EF \quad (11)$$

where $Electricity_{potential}$ is the installed capacity of electricity from biogas for each region (MW), 7200 is the annual operating hours (hr) of biogas plant, and EF is the CO_2 emission factor as follows:

Baseline EF: Peninsular Malaysia, 0.585 t CO_2 $MWhr^{-1}$; Sabah and Wilayah Persekutuan Labuan, 0.522 t CO_2 $MWhr^{-1}$ and Sarawak, 0.330 t CO_2 $MWhr^{-1}$ (MGTC, 2019).

Status of Biogas Capture and Utilisation

Analysis on status of biogas capturing facilities and their utilisation approaches in the Malaysian POMs was conducted via a survey using previously collected database in 2021. *Table 2* shows the location of the biogas plant installed in 135 POMs nationwide. Status and information of these biogas plants were collected and verified via a phone call to either the millers directly, representative of mill's parent company or RE developers that have successfully built, owned and operated the biogas plants. Questions to respondents were on status of biogas plant, technology used, type of utilisation, installed capacity (MW) and future planning, if any for those biogas plants currently on flaring option. The findings were summarised as number of mills plus percentage biogas utilisation or number of mills plus total installed capacity (MW).

TABLE 2. NUMBER OF BIOGAS PLANT IN PALM OIL MILLS (BY STATE) IN 2021

State	No. of mills with biogas plant	State	No. of mills with biogas plant
Johor	23	Perak	17
Kedah	4	Pulau Pinang	1
Kelantan	1	Sabah	34
Melaka	1	Sarawak	14
Negeri Sembilan	6	Selangor	6
Pahang	25	Terengganu	3

RESULTS AND DISCUSSION

Volume of Wastewater (POME)

As of December 2021, there were 451 POMs in operation nationwide with a total approved annual FFB processing capacity of 112.91 million tonnes. The total FFB processed in 2019 (425 mills), 2020 (457 mills) and 2021 (451 mills) were 98.28, 96.09 and 90.53 million tonnes, respectively, and thus a depreciation trend observed nationally in milling capacity utilisation from 87.0%, 82.3% to 77.6%. The approved annual FFB processing capacity and actual FFB processed by the mills equipped with biogas plant in 2021 was 40.10 and 29.93 million tonnes, respectively. *Figure 1* and *Table 3* show the estimated amount of POME generated from the Malaysian POMs from 2019 to 2021.

The POME generation decreased from 63.88 to 58.84 million m^3, with mean value of 61.72 million m^3 during these periods, 2019-2021 (*Figure 1*). This big volume is indicative of a huge availability of POME as reported in previous years; 60.88 and 58.50 million m^3 in 2015 and 2018, respectively (Chia *et al.*, 2020; Choong *et al.*, 2018). For 135 mills equipped with biogas plant, 19.45 million m^3 of POME were anaerobically treated in closed digesters in 2021 (*Table 3*). The higher POME generation in 2019 was attributed to higher FFB yield and the subsequent processed fruits which consumed more water during the milling process, compared to the lower FFB productivity for the two consecutive years associated with COVID-19 pandemic. Generation of POME is dependent on the amount of FFB processed. Restricted movement of COVID-19 and labour shortage have significantly contributed to the declining trend of FFB yield and FFB processed in 2020 and 2021 (Parveez *et al.*, 2021). Such occurrence brought about lesser amount of water used for milling activities, and thus lower POME generation compared to 2019. The COVID-19 pandemic has also caused immediate and adverse impact to the country's POME-based biogas development.

A conventional mill requires an average of 1.0-1.2 m^3 water for every tonnes of FFB processed (Kospa *et al.*, 2017), where >50% of water is discharged as POME (Loh *et al.*, 2013). The annual trend of FFB processed, either at national or individual mill level, is an important parameter needed to plan, forecast and design appropriate biogas plant capacity and its potential utilisation options.

Biogas Production from Palm Oil Mill Effluent

Figure 1 and *Table 3* also show the estimated total volume of biogas production via business-as-usual scenario, *i.e.*, AD of POME in all POMs nationwide in 2019-2021. Based on 28 m^3 m^{-3} POME, the biogas production potential significantly decreased from 1789 to 1648 million m^3 during these periods. Similarly, as biogas production is proportionate to the amount of FFB processed, the total volume of POME also showed downward trend for the past three years. The biogas yield of 28 m^3 m^{-3} POME, for estimating biogas potential, is an established biogas generation rate for POME obtained from comprehensive experimental and field monitoring data; as demonstrated by previous studies (Lim and Biswas, 2019; Muzzammil and Loh, 2020). The range of biogas yield is 24-32 m^3 m^{-3} POME using various

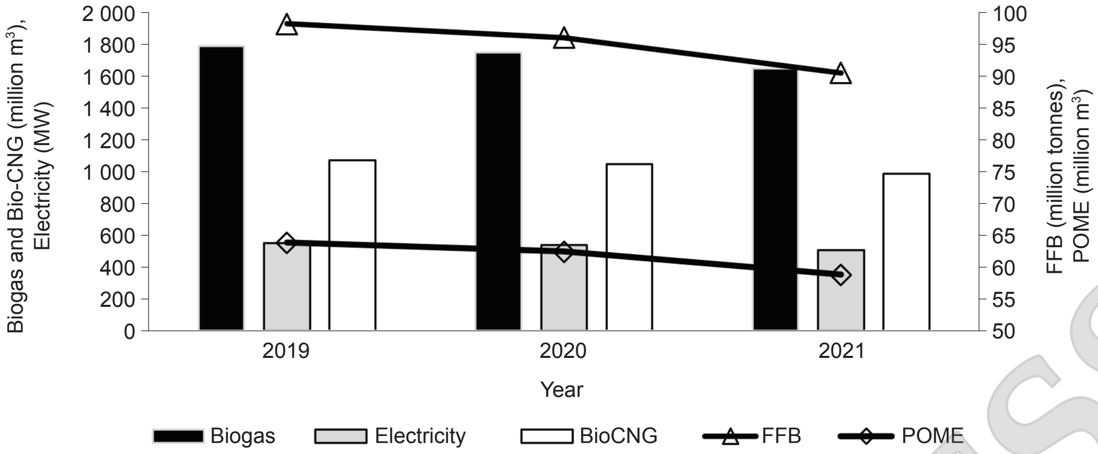

Figure 1. Estimated volume of palm oil mill effluent (POME), biogas and bio-compressed natural gas (Bio-CNG), and renewable electricity potential derived from fresh fruit bunches (FFB) processed in the Malaysian palm oil mills (2019-2021).

TABLE 3. ESTIMATED ANNUAL RENEWABLE ENERGY POTENTIAL FROM FRESH FRUIT BUNCHES (FFB) PROCESSED, PALM OIL MILL EFFLUENT (POME) AND BIOGAS GENERATION

Item	2019	2020	2021	135 mills with biogas plant (2021)
FFB processed, million tonnes	98.28	96.09	90.53	29.93
POME production, million m^3	63.88	62.46	58.84	19.45
Biogas generation, million m^3	1 789	1 749	1 648	545
Energy potential, million MJ	35 780	34 980	32 960	10 895
Diesel equivalent, million L	1 018	995	938	310
Natural gas equivalent, million m^3	1 022	1 000	942	311
Electricity (installed capacity), MW	552	539	508	168
Bio-CNG, million m^3	1 073	1 049	989	327

technologies (Muzzammil and Loh, 2020). If biogas is not captured in POMs, the potential RE is wasted. More critically, CH_4 and CO_2 in biogas are emitted to the atmosphere contributing to GHG emissions and causing global warming. The capturing facilities established from 135 mills could prevent about 545 million m^3 biogas from being released to the atmosphere, which means 33% RE potential have been tapped from the overall potential in 2021.

Renewable Energy (Biogas) Potential from Palm Oil Mill Effluent

Table 3 summarises the potential of various types of RE that can be derived from biogas. Biogas contains an average of 60%-70% CH_4, 30%-40% CO_2 and 800-1500 ppm H_2S (Loh *et al.*, 2017). Energy potential or calorific value of biogas relies on CH_4 content as a combustible gas. The calorific value of biogas containing 55%-65% CH_4 is typically between 19.7-23.3 MJ m^{-3} (Kaparaju and Rintala, 2013). Assuming that biogas from POME has a calorific value of 20 MJ m^{-3}, the total annual energy potential from the generated biogas has decreased from 35 780 MJ in 2019 to 32 960 MJ in 2021. More importantly, these values are equivalent to more than 938 million L diesel or 942 million m^3 natural gas annually, if the biogas is fully harnessed as an alternative to fossil fuels. Biogas is typically used for heat or power generation, or by combining both the energy sources in a combined heat and power (CHP) plant via combustion process. A direct method to exploit biogas as RE in the forms of heat or steam is through either package boiler, burner or cofiring with biomass in palm oil mill boiler (Loh *et al.*, 2017).

Internal combustion engine or gas engine is commonly deployed for commercial electricity generation from biogas. Raw biogas is pre-treated to remove H_2S and moisture prior to being burnt in the gas engine. The heat generated from this conversion system can be recovered and used as energy. Other energy conversion systems for biogas to electricity generation are gas or micro gas turbine, diesel generator (via cofiring) and fuel cell (Kaparaju and Rintala, 2013). The potential annual electricity generation from POME-based biogas is estimated to be 3.65-3.97 million MWhr or 508-552 MW installed capacity if all the captured biogas is used for electricity generation. Power generation capacity is dependent on the thermal efficiency of a gas engine. Studies reported that thermal efficiencies of natural gas-based and biogas-based engines can range between 38%-42% and 28%-30%, respectively (Firdaus *et al.*, 2017). The country's total installed capacity for electricity generation in 2019 was 36 182.8 MW, consisted mainly of fossil-based power (78.1%), hydropower (17.1%) and renewables (4.8%) including 0.4% from biogas (Suruhanjaya Tenaga, 2021). Current scenario indicates that electricity potential of biogas from POME could contribute about 1.4%-1.5% to the national installed capacity mix and about 4.0% to the RE share (12 916 MW) target by 2025 under the Malaysia Renewable Energy Roadmap (SEDA, 2022). The roadmap also targets 40.0% RE share or 17 996 MW in 2035.

An emerging RE potential of biogas is the upgraded methane-rich Bio-CNG, a natural gas like fuel which is more versatile for effective and wider applications. The process involves multi-stage procedures by primarily removing CO_2, H_2S and moisture in raw biogas to ultra-low purification level using physical, chemical and biological methods, which leads to CH_4 enrichment. H_2S removal from POME-based biogas for Bio-CNG production has been carried out using a combined biological and physical adsorption of activated carbon, followed by chemical absorption to achieve 99% of removal efficiencies (Nasrin *et al.*, 2020; Park, 2021). Membrane technology used for CO_2 removal from POME-based biogas has enabled 94% of removal efficiencies with 98% CH_4 content in the resultant Bio-CNG (Park, 2021). Other major CO_2 removal technologies are pressurised water scrubber, pressure and vacuum swing adsorption, *etc*.

Potential of Bio-CNG from POME was estimated to be about 1073, 1049 and 989 million m^3 in 2019-2021. These values are equivalent to 35-38 million MMBTU Bio-CNG per year. In 2018, natural gas consumption from pipelines supplied by Gas Malaysia Berhad and Sabah Energy Corporation Sdn. Bhd. was 201 MMBTU (Suruhanjaya Tenaga, 2021). Assuming that all the captured biogas is upgraded to Bio-CNG and supplied to the natural gas pipelines nationwide, about 17%-19% of the piped gas can be potentially supplied to consumers. Feeding and funding mechanisms, infrastructure and logistic supports as well as the governmental frameworks are needed to further accelerate the development of Bio-CNG plant and natural gas blending via the pipelines.

The potential RE, as technically estimated above, can only be realised if all 451 POMs were installed with biogas capturing facilities while treating POME at the same time to meet the regulatory discharge limits. As of December 2021, some 135 POMs installed and captured biogas for various energy utilisation including just flared the captured biogas. This represents about 30% from the total number of POMs operated in 2021. *Table 3* shows the potential energy, electricity and Bio-CNG of 10 895 million MJ, 168 MW and 327 million m^3, respectively from 135 mills equipped with biogas facilities, based on 29.93 million tonnes FFB processed and 19.45 million m^3 POME generated. These values represented 33% of the total RE potential available from POME generated in 2021, and thus huge biogas potential is untapped in the country.

Greenhouse Gases (GHG) Emissions and Potential GHG Savings

Table 4 summarises the estimated GHG emissions from conventional POME treatment system from 2019 to 2021. The amount of CH_4 generated from AD of POME was 814 496, 796 346 and 750 268 t yr^{-1}, respectively. These values are equivalent to 18.76-20.36 million tonnes CO_2eq yr^{-1} nationwide, based on 25 times greater global warming potential of CH_4 than CO_2. It is slightly higher than the life cycle GHG emissions of 17.80, 17.15 and 16.24 million tonnes CO_2eq yr^{-1} calculated based on 896.48 kg CO_2eq t^{-1} CPO (Subramaniam *et al.*, 2010). The total GHG emissions from POME nationwide contributed about 6.8%-7.5% to the country's total GHG emissions in 2020 (272.61 million tonnes CO_2eq) (Ritchie *et al.*, 2020).

Uncaptured biogas is one of the dominant contributors of GHG emissions along the palm oil supply chain. It contributes about 50% to the total GHG emissions of CPO production (Krishnan *et al.*, 2017), with the remaining dominated by chemical fertilisers produced and used in oil palm plantations (Subramaniam *et al.*, 2021). Biogas trapping facilities give huge savings and greatly address the GHG emissions from POMs. The potential to generate and capture CH_4 from biogas plants operated in 135 POMs was 247 988 t yr^{-1} or about 33.1% from the total CH_4 emitted nationwide. Thus, 66.9% of biogas was still released to the atmosphere in 2021. Biogas production is proportionate to GHG emissions and likewise for biogas capturing *vis-à-vis* GHG savings. The higher amount of biogas is produced and captured, the more GHG emissions is mitigated, so does the GHG savings.

Capturing biogas for energy recovery provides two types of savings, namely avoiding biogas from emitting to the atmosphere and substituting fossil fuel with biogas fuel (Subramaniam *et al.*, 2021). If all mills were equipped with biogas plants, the GHG savings potential could be approximately 15.0-16.3 million tonnes CO_2eq annually. These values can be translated into 5.5%-6.0% potential avoided CO_2 emissions from the country's total GHG emissions in 2020 (Ritchie *et al.*, 2020). The calculated actual

TABLE 4. TOTAL METHANE AND GREENHOUSE GASES (GHG) EMISSIONS, AND POTENTIAL GHG SAVINGS FROM PALM OIL MILLS (POMS) IN MALAYSIA

	POMs nationwide			135 POMs with biogas plant
Year	**2019**	**2020**	**2021**	**2021**
Methane emissions, t yr^{-1}	814 496	796 346	750 268	(247 988)
GHG emissions, million tonnes CO_2eq yr^{-1}	20.36	19.91	18.76	(6.20)
Potential GHG savings, million tonnes CO_2eq yr^{-1}	16.29	15.93	15.00	4.96

potential of GHG savings from 135 mills was 4.96 million tonnes CO_2eq yr^{-1}, equivalent to about 1.8% of the country's GHG emissions in 2020, compared to 1.6% emission reduction in 2013 (Susskind *et al.*, 2020). Thus, biogas capture is an established GHG mitigation initiative, which also facilitates the country's commitment to reduce carbon emissions intensity per unit of gross domestic product (compared to 2005 levels) by 45% in 2030 (SEDA, 2022). *Table 5* summarises the potential of GHG savings via displacement of fossil fuel for electricity generation using biogas from POME.

Table 5 shows that an additional 1.89 million tonnes CO_2eq yr^{-1} of GHG savings could be accomplished through fossil fuel displacement if all POMs in the country capture biogas to generate electricity. Specifically, the 135 mills operated with biogas plant contribute to 0.66 million tonnes CO_2eq yr^{-1} GHG savings through electricity generation. In total, the country could potentially mitigate 16.89 and 5.62 million tonnes CO_2eq yr^{-1} of GHG associated with POME-based biogas capture for electricity utilisation from 451 mills and 135 biogas-based mills, respectively. Potential GHG savings from biogas utilisation as electricity is relatively lower than activity in biogas capture itself, depending much on emission factor of the displaced fossil fuels.

Status of Biogas Capture and Utilisation

Technology Used for Biogas Capture in Palm Oil Mills

Based on the latest figure of 135 mills equipped with biogas plant in 2021, two type of biogas capture technology commercially used are closed digester tank (66 mills, 49%) and covered lagoon technology (65 mills, 48%). The remaining 4 mills opted for a combined technology (hybrid system, 3%). These findings indicated a relatively similar deployment of closed digester tank and covered lagoon technology due to growing interests in the latter. For the past 10 years, covered lagoon technology has been improvised in terms of design and process efficiency, leading to better operation and yield performance, compared to the basic system that was widely promoted during the Clean Development Mechanisms (CDM) period (2005-2012) (Loh *et al.*, 2017).

AD of POME using an improved covered lagoon technology has fetched high COD removal efficiencies of >85% (Yap *et al.*, 2020). These values are comparable to the typical continuous stirred tank reactor technology (CSTR) (Irvan *et al.*, 2018). The technology is also capable of generating 25-30 m^3 biogas m^{-3} POME, which is within the range offered by the CSTR technology (Muzzammil and Loh, 2020). High treatment efficiency can be accomplished by improving the mixing mechanisms via either sludge return, gas recirculation or multiple feeding system. Other factors such as lower capital expenditure (CAPEX) and operational expenditure (OPEX), and higher POME and biogas storage capacity are

TABLE 5. POTENTIAL OF GREENHOUSE GASES (GHG) SAVINGS VIA BIOGAS CAPTURE AND ELECTRICITY GENERATION FROM PALM OIL MILLS (POMS) IN 2021

Item	451 POMs nationwide	135 POMs with biogas plant
Potential savings (biogas capture), million tonnes CO_2eq.	15.0	4.96
Potential savings from electricity generation at 7 200 hr yr^{-1}, million tonnes CO_2eq $MWhr^{-1}$		
Peninsular Malaysia (EF: 0.585)	1.18 (279 MW)	0.47 (112 MW)
Sabah (EF: 0.525)	0.45 (119 MW)	0.14 (37MW)
Sarawak (EF: 0.330)	0.26 (110 MW)	0.05 (19 MW)
Saving from fossil fuel displacement, million tonnes CO_2eq yr^{-1}	1.89 (508 MW)	0.66 (168 MW)
Total (million tonnes CO_2eq yr^{-1})	16.89	5.62

Note: EF - Emission factor.

considered as an added advantage to the covered lagoon technology. Nevertheless, the closed digester tank is still the preferred technology for mills with limited land areas. The survey also showed that 4 mills deployed a hybrid system, *i.e.*, by combining both the technologies to produce and capture the biogas. The hybrid AD system is operated either in series or parallel mode. Apart from yield maximisation, this approach is undertaken by developers to upgrade the biogas plant for better performance.

Biogas Utilisation in Palm Oil Mills

Figure 2 summarises major utilisation pathway of biogas capture in POMs. Out of 135 mills with biogas plant, 87 plants (64%) venture into electricity generation, 15 plants (11%) utilise the biogas for steam/ heat or CHP generation, 32 plants (24%) have yet to use the biogas for energy generation and one plant upgrades and purifies the raw biogas for Bio-CNG production only. As of December 2021, the total installed capacity of POME-based biogas power plants was 138.51 MW, compared to the total potential of 168 MW estimated from 135 mills with biogas plant (*Table 3*). For this purpose, all the plants deployed a typical internal combustion engine, except one mill which opted for a micro-gas turbine to generate electricity for internal or off-site uses. For the 87 mills producing electricity from biogas, several utilisation configurations and multiple uses have been adopted. *Figure 3* shows a detailed utilisation breakdown of generated electricity from the POME-based biogas power plant in Malaysia.

Of the 87 mills with biogas plant for electricity generation, 43 plants are grid-connected under the national Feed-in Tariff (FiT) program including three plants which also channel part of the electricity generated to the mills for internal use, two plants for rural electrification, 35 plants for internal use in the mills or integrated palm oil complexes and another seven mills for a combined electricity and

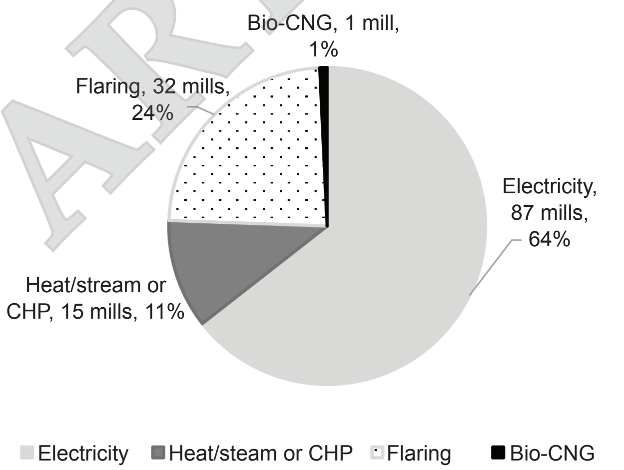

Figure 2. Major biogas utilisation in palm oil mills in Malaysia.

steam generation. POME-based biogas plant for FiT has made up 57.5% or 79.69 MW of the total capacity realised nationwide. Biogas from POME contributes the biggest share, approximately 72%, to the cumulative installed grid-connected biogas plant capacity of 110.59 MW in 2020 (SEDA, 2021). Currently, electricity generation for FiT is the most deployed biogas utilisation option by the millers, mainly driven by the attractive 16-year fixed basic FiT rate and bonuses.

Previously, the maximum FiT rate was RM0.4669 $kWhr^{-1}$ consisting of RM0.3184 $kWhr^{-1}$ for basic rate and additional bonuses of RM0.1485 $kWhr^{-1}$, where applicable (Loh *et al.*, 2017). SEDA has introduced e-bidding exercise in 2018 for securing the lowest possible basic FiT rate of biogas. As of 2020, 3 e-bidding exercises have been held with an average basic FiT bid rate of RM0.2567-RM0.2599 $kWhr^{-1}$ (SEDA, 2021). The FiT quota for biogas is limited and competitive, mainly relied on the RE fund collected from electricity consumers nationwide, except for Sarawak. Besides, the potential of POMs for grid connection is also limited, depending mainly on the distance of the mills to the interconnection point, local load demand and safety aspects. Preliminary feasibility study is needed prior to conducting a full power system study which is very costly and may not be worthy of effort if the outcome is not promising (Loh *et al.*, 2017).

Two biogas power plants with a combined capacity of 2.8 MW have been operated by FGV Holdings Berhad in two of their POMs, which supply the generated electricity to the nearby settlement areas and townships at Felda Umas and Felda Sahabat in Sabah (FGV, 2020). This initiative reduces dependency on high-cost diesel-generated electricity for rural areas. To date, the total installed capacity from the POME-based biogas for off-site uses via the FiT and rural electrification programme was 82.49 MW, which was equivalent to 60% of the total installed capacity nationwide in 2021. This indicates that biogas from POME has huge potential for off-site electricity generation. It is anticipated that more POME-based biogas power plants will be built and connected either to the national or local grids in the future, if additional FiT quota or incentives for rural electrification is made available for deployment by palm oil millers.

The electricity generated from biogas has also been widely used internally for operation of POMs, and more so via integration of palm oil complexes consisting of mill, estates, workshop, downstream business activities (including Bio-CNG), workers housing and community areas. This approach could cater for the energy required to spur economic activities and improve livelihoods of the communities within mill vicinity. Currently, seven mills have adopted multiple uses for the captured

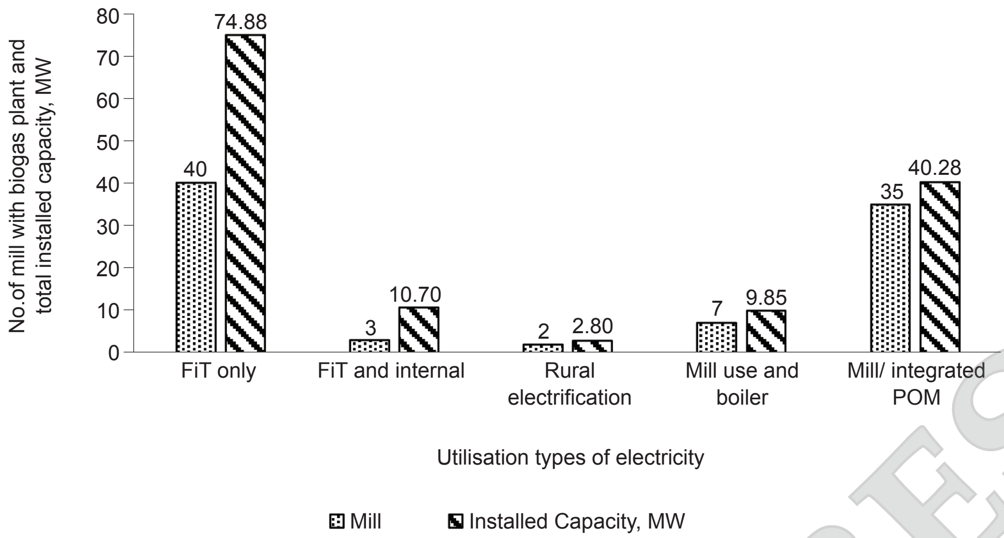

Figure 3. Utilisation configuration for electricity generation from biogas in the palm oil mills in Malaysia.

biogas, *i.e.*, by combining electricity generation and biogas cofiring, for achieving better economic viability. Briefly, the electricity generated in these mills has been used mainly to support milling operation during start-up and shutdown as well as for non-processing period. Any biogas in excess is supplied to the biomass-fired boiler during processing hours.

The captured biogas is also used as fuel displacement to generate steam, heat or CHP, as deployed by 15 plants in 2021. Typically, biogas is cofired in biomass boilers (serve as a CHP plant) to generate steam and electricity for milling process. The process displaces biomass fuel, particularly palm kernel shell which can be sold as a solid fuel and feedstock for value-added products, and at the same time facilitates reduction of particulate emissions from boiler chimney. For those mills integrated with palm oil refinery, biogas is used in package boiler or chiller to generate steam and chilled water for refining process (Loh *et al.*, 2017). This kind of activity has resulted in substantial cost savings on fossil fuel. Besides, raw biogas can be sold to nearby industry that requires fuel for heat generation. This has been commercially demonstrated by BBC Palm Oil Mill in Sarawak for supplying the raw biogas to the brick factory located next to the mill (Lim and Biswas, 2019).

Currently, 32 mills are not utilising the captured biogas and opted to merely flare it. Most of these plants were developed during the CDM period (2005-2012) with profitable earning of certified emission reduction credits (Loh *et al.*, 2017). This activity continues to be business as usual post-CDM commitment. Biogas flaring is typically a temporary option for those newly-commissioned or long-established biogas plants in order to comply with existing licensing criteria mandated for new mills and mills requiring capacity expansion. These mills have yet to finalise their utilisation option or may not even opt for any energy recovery soon due to constraints such as low biogas yield or small plant capacity, and thus is deemed economically infeasible. For future deployment of captured biogas, four plants will commit to FiT, four plant will generate electricity for internal use and another plant for CHP.

Limited onsite utilisation within a mill also contributes to slow development of biogas capturing facility as well as underutilised or wasted biogas energy recovery (Loh *et al.*, 2022). One of the promising ways to optimise and diversify biogas uses for off-site applications is by upgrading raw biogas to Bio-CNG or biomethane (Tan and Lim, 2019). To date, two commercial Bio-CNG plants from POME have been installed at POMs to demonstrate their commercial potential. Each plant has the capacity to produce 9600 and 5000 m^3 day^{-1} concentrated compressed CH_4, respectively (Loh *et al.*, 2017). Bio-CNG is an emerging alternative to typical biogas utilisation option, in particular for those mills located near to industrial area or natural gas pipelines, and infeasible for grid connection. The product can be used either on-site, transported using compressed natural gas trailer to potential users' site (mobile pipeline), injected to gas pipeline and as alternative to vehicle fuel. Since biogas upgrading involves an advanced technology, high CAPEX and OPEX are required compared to other biogas utilisation routes. It is anticipated that more Bio-CNG plants will be developed and injected to the natural gas pipelines with the implementation of third party access in the Gas Supply (Amendment) Act 2016, as part of the country's natural gas market liberation initiatives (Hoo *et al.*, 2020).

Limitations and Improvements of Biogas Utilisation: Safety, Environmental and Economic

Potential of biogas capture system for various energy applications is promising but there are still limitations that need to be addressed from safety, environmental and economic perspectives. Current biogas plants have only minimal safety feature such as flame arrestor and safety relief valve without sophisticated risk management tool, and thus it is important for developers to ensure the highest possible level of safety or minimum risks to human health and safety, and the environment (Gomez, 2013). There are adequate dedicated Malaysian Standard (MS), namely MS 2581:2014 on production of biogas - code of practice or guidelines on safety that are available for adoption in this business (Loh *et al.*, 2017). The existing MS or other guidelines can be improved further while new MS on safety of biogas utilisation also should be developed. As safety risks and hazards may also be associated with the operators, safety training modules and awareness programme must be regularly improved and conducted (Gomez, 2013).

Environmental benefits of biogas capture and utilisation are manifold and significant. However, the resultant environmental performance may be limited or jeopardised due to inefficiency of biogas plant operation, possible emissions from inefficient capturing facilities, leakages, poor POME handling during pre- and post-AD treatment from open ponding system and odour emissions (Chin *et al.*, 2013; Mahmod *et al.*, 2023). CH_4 slip may also occur during incomplete combustion of gas engine and off-gas from Bio-CNG plant (Gomez, 2013). The environmental performance related to biogas plant efficiencies can be improved by adopting the most efficient latest technology including to fully automatise and digitalise the biogas plant not just on the operation, but also process monitoring and quality control via the Fourth Industrial Revolution concepts, *i.e.*, internet of things, artificial intelligence, *etc*. (Cinar *et al.*, 2021). Adoption of these concepts also can contribute to better economic and improved safety aspects towards smart biogas plant in POMs.

Despite numerous end-use applications with varying level of economic returns, biogas utilisation either in POMs or for off-site uses is limited. This is mainly attributed to lack of energy needs and surplus biomass energy in typical POMs, logistics issues and limited infrastructures for off-site applications (Nasrin *et al.*, 2022; Tan and Lim, 2019). Grid-connected biogas plant is dependent on FiT quota which is very limited and only eligible for 16 years (Tan and Lim, 2019). Besides, the FiT programme is not available in Sarawak (Chin *et al*., 2013). Economic returns are subjected to economic of scale which is dependent on the capacity of the biogas plant or the mills, types of biogas utilisation or pathway and location of the mills to the end users. Therefore, biogas utilisation path needs to be diversified and extensively exploited to expand potential application and improve economic returns. Business model of biogas plant needs to be strategised considering all the economic factors including to factor in environmental cost mechanism such as carbon credit scheme for an attractive revenue (Sharvini *et al.*, 2022). Improvement of the governmental frameworks, supports, incentives and infrastructures are required, in particular in new business opportunity such as Bio-CNG.

CONCLUSION

The mitigation activity via biogas capture and utilisation improves sustainability performance of the palm oil industry and facilitates the understanding and commitment on global issues related to energy crisis and global warming. In this study, biogas from POME shows huge potential RE and GHG savings. The palm oil industry could contribute approximately 1.5% and 4.0% to the national installed capacity and the RE share target in Malaysia by the year 2025, respectively with substantial GHG savings of 15 million tonnes CO_2eq yr^{-1} if all POMs capture and utilise the biogas. At present, 30.0% of POMs have installed biogas plants with 33.0% energy recovery rate from the overall estimated potential. More proactive and synergised efforts are required from the industry players to harness the huge untapped potential of RE from biogas in enhancing sustainable image of the industry. Future research should emphasis on new and emerging biogas end-uses such as Bio-CNG, liquefaction and biohydrogen for commercial adoption. This kind of new business opportunities could only be expediated by strengthening the governmental frameworks and supports such as infrastructure and incentives.

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