TECHNO-ECONOMIC ASSESSMENT AND ENVIRONMENTAL ANALYSIS OF BIO-COMPRESSED NATURAL GAS PRODUCTION FROM PALM OIL MILL EFFLUENT

NASRIN BIN ABU BAKAR

FACULTY OF ENGINEERING
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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

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Field of Study: Engineering and Engineering Trades (Chemical and Process)

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TECHNO-ECONOMIC ASSESSMENT AND ENVIRONMENTAL ANALYSIS OF BIO-COMPRESSED NATURAL GAS PRODUCTION FROM PALM OIL MILL EFFLUENT

ABSTRACT

There were 451 palm oil mills in Malaysia and these mills generated about 60 million m^3 of palm oil mill effluent (POME) in the year 2021. Due to its high organic content, POME needs to be treated before being discharged to the water bodies within regulatory discharge limits. Conventionally, anaerobic digestion method via open ponding or tank systems are used for this purpose where the treatment efficiency is low and the biogas produced is not recovered. In the last two decades, capturing biogas using closed anaerobic digester are becoming acceptable practice as an integrated treatment of POME and biogas capture as a mean to reduce greenhouse gases (GHG). The captured biogas is typically used for heat and power generation. In recent time, upgrading biogas for biomethane or bio-compressed natural gas (Bio-CNG) production has emerged as an alternative to biogas utilisation in Malaysia. However, a detailed technical, economic and environmental assessment for commercial Bio-CNG production, is yet to be established in Malaysia, which forms the justification of this work. Potential biogas volume, installed electricity capacity and Bio-CNG production from entire palm oil mills (451 mills) in Malaysia in 2021 were approximately 1648 million m^3, 508 MW and 988 million m^3 Bio-CNG, respectively. A total of 135 mills were installed with biogas plant in 2021 and therefore only 33% of the full energy potential was realized. In terms of utilization, 87 mills utilise the biogas for electricity generation, 15 mills for steam or combined heat and power generation, and only a single mill for Bio-CNG production. However, 32 mills were just flaring the biogas generated without energy recovery and used it for the purpose of methane (CH_4) emission mitigation strategy. As a proof of concept, a 400 m^3/hr Bio-CNG plant was developed and evaluated in a palm oil mill located at Kuala Kubu Bahru, Selangor. The Bio-CNG production process which was based on combined biological and physical methods, and membrane technology achieved hydrogen sulphide (H_2S) and carbon dioxide (CO_2) removal efficiencies of 99 and 92.2%, respectively. The produced Bio-CNG was found to contain about 94 vol.%, 3 vol.%, 0.5 vol.% and 3 vol.% of CH_4, CO_2, O_2 and N_2 respectively with H_2S at a trace level of 3 ppm, resulting in significant increase of calorific value from 20 MJ/m^3 to 35 MJ/m^3. These properties are also comparable to natural gas quality. The economic analysis conducted for Bio-CNG plant integrated with existing biogas plant indicated that an approximate 14% internal rate of return with a payback period about 6 years for a mill with 54 tonnes per hour capacity. The Life Cycle Impact Assessment carried out showed that the environmental impacts of the Bio-CNG production were global warming, fine particulate matters formation, fossil and mineral resources scarcity. These were due to the plants' heavy dependence on the grid-connected electricity. In conclusion, Bio-CNG is technically, economically, and environmentally viable business alternative to biogas offsite utilisation.

Keywords: Sustainability, greenhouse gases, renewable energy, electricity, biomethane.

PENILAIAN TEKNO-EKONOMI DAN ANALISA ALAM SEKITAR KE ATAS PENGHASILAN BIOGAS ASLI TERMAMPAT DARIPADA EFLUEN KILANG SAWIT

ABSTRAK

Terdapat sebanyak 451 kilang kelapa sawit di Malaysia dan kilang-kilang ini menghasilkan kira-kira 60 juta m^3 efluen kilang kelapa sawit (POME) pada tahun 2021. Oleh kerana kandungan organiknya yang tinggi, POME perlu dirawat sebelum dilepaskan ke alur air di bawah had pelepasan yang dibenarkan. Sistem rawatan konvensional efluen sawit adalah berasaskan kaedah pencernaan anaerobik menggunakan sistem kolam atau tangki terbuka. Kadar keberkesanan dan kecekapan kaedah rawatan ini adalah rendah dan biogas yang terhasil tidak diperangkap. Sejak dua dekad yang lalu, sistem pemerangkapan biogas melalui kaedah pencernaan anaerobik tertutup mula diterima secara meluas sebagai loji rawatan bersepadu POME dan pemerangkapan biogas bertujuan untuk mengurangkan kesan gas rumah hijau (GHG). Tipikal penggunaan biogas adalah untuk penjanaan haba dan elektrik. Sejak kebelakangan ini, peningkatan kualiti biogas melalui penghasilan biometana atau biogas asli termampat (Bio-CNG) telah muncul sebagai alternatif baru kepada penggunaan biogas di Malaysia. Walau bagaimanapun, potensi dan kesan teknikal, ekonomi dan alam sekitar bagi pengeluaran Bio-CNG secara komersial, masih belum dinilai sepenuhnya di Malaysia, mendorong kepada keperluan kajian ini dilakukan. Potensi biogas, kapasiti elektrik terpasang dan pengeluaran Bio-CNG daripada keseluruhan kilang kelapa sawit (451 kilang) di Malaysia masing-masing adalah dianggarkan berjumlah 1648 juta m^3, 508 MW dan 988 juta m^3 Bio-CNG. Pada masa ini sebanyak 135 kilang telah memasang loji biogas dengan potensi tenaga terhasil sebanyak 33% daripada jumlah keseluruhan tenaga yang tersedia untuk direalisasikan. Dari segi penggunaan, 87 kilang menggunakan biogas untuk penjanaan elektrik, 15 kilang untuk penghasilan stim atau gabungan haba dan penjanaan kuasa, dan hanya satu kilang yang menghasilkan Bio-CNG. Walau bagaimanapun, 32 kilang hanya membakar biogas yang dihasilkan tanpa penjanaan tenaga sebagai strategi mitigasi pelepasan gas metana ke atmosfera. Bagi tujuan merealisasikan konsep ini, sebuah loji pengeluaran Bio-CNG berkapasiti 400 m^3/sejam telah dibangunkan dan dinilai di sebuah kilang kelapa sawit yang terletak di Kuala Kubu Bahru, Selangor. Proses pengeluaran Bio-CNG yang menggabungkan kaedah biologi dan fizikal, dan teknologi pemisahan membran berjaya mencapai kecekapan penyingkiran gas hidrogen sulfida (H_2S) dan karbon dioksida (CO_2) masing-masing sebanyak > 99 dan 92.2%. Bio-CNG yang dihasilkan didapati mengandungi kira-kira 94% CH_4, 3% CO_2, 0.9% O_2 dan 3% N_2 dengan komposisi H_2S pada tahap serendah 3 ppm. Komposisi ini memberikan peningkatan ketara nilai kalori daripada 20 MJ/m^3 kepada 35 MJ/m^3, setanding dengan kualiti gas asli. Analisis ekonomi yang dijalankan untuk loji Bio-CNG yang diintegrasikan dengan loji biogas sedia ada menunjukkan bahawa kadar pulangan dalaman (IRR) sebanyak 14% dengan tempoh bayaran balik (PBP) selama 6 tahun untuk kilang dengan kapasiti pemprosesan 54 tan sejam. Penilaian Impak Kitaran Hayat yang dijalankan menunjukkan bahawa kesan alam sekitar pengeluaran Bio-CNG adalah pemanasan global, pembentukan bahan zarah halus, kekurangan sumber fosil dan mineral. Ini disebabkan oleh pergantungan tinggi loji Bio-CNG pada bekalan elektrik daripada grid nasional. Kesimpulannya, Bio-CNG adalah alternatif penggunaan komersial biogas yang berpotensi dari segi teknikal, ekonomi, dan mesra alam yang berdaya maju bagi mempelbagaikan penggunaan biogas di luar kilang kelapa sawit.

Kata kunci: Kelestarian, minyak sawit, kegunaan biogas, elektrik, gas asli termampat.

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AD	:	anaerobic digestion
AHR	:	anaerobic hybrid reactor
AN	:	ammoniacal nitrogen
AnEG	:	anaerobic expanded granular sludge bed
AnMBR	:	anaerobic membrane bioreactor
BAU	:	business as usual
Bio-CNG	:	bio-compressed natural gas
Bio-LNG	:	bio-liquified natural gas
BOD	:	biological oxygen demand
CABR		carrier anaerobic baffled reactor
CAPEX	:	capital expenditure
CDM	:	Clean Development Mechanisms
CER	:	carbon emission reduction
CHP	:	combined heat and power
COD	:	chemical oxygen demand
CPO	:	crude palm oil
CSTR	:	continuous stirred tank reactor
CV	:	calorific value
DCF	:	discounted cashflow
DOE	:	Malaysian Department of Environment
EF	:	emission factors
EFB	:	empty fruit bunch
EGSB	:	expanded granular sludge bed
FFB	:	fresh fruit bunches
FiT	:	Feed-in Tariff

GC : gas chromatography

GCV : gross calorific value

GHG : greenhouse gases

GWP : global warming potential

HDPE : high-density polyethylene

HRT : hydraulic retention time

IAAB : integrated anaerobic-aerobic bioreactor

IPCC Intergovernmental Panel on Climate Change

IRR : internal rate of return

ISO : International Standard Organisation

LCA : life cycle assessment

LCI : life cycle inventory

LCIA : life cycle impact assessment

LLDPE : linear low density polyethylene

MAS : membrane anaerobic system

MPOB : Malaysian Palm Oil Board

MRE : Mill raw effluent

MyRER : Malaysia Renewable Energy Roadmap

NPV : net present value

O&G : oil and grease

OLR : organic loading rate

OPEX : operational expenditure

PBP : payback period

PEIO : primary energy input to output

PKS : palm kernel shell

POM : palm oil mill

POME	:	palm oil mill effluent
PSA	:	pressure swing adsorption
RE	:	renewable energy
SCABR	:	suspended closed anaerobic bioreactor
SS	:	suspended solid
SOB	:	sulphur oxidizing bacteria
TAnMBR	:	thermophilic anaerobic membrane bioreactor
TN	:	total nitrogen
TS	:	total solid
TSS	:	total suspended solid
TVS	:	total volatile solid
UAMAS	:	ultrasonic-assisted membrane anaerobic system
UASB	:	up-flow anaerobic sludge blanket
UASB HCPB	:	up-flow anaerobic sludge blanket hollow centered packed bed
UASFF	:	up-flow anaerobic sludge fixed film
VFA	:	volatile fatty acids
VSS	:	volatile suspended solid

CHAPTER 1: INTRODUCTION

1.1 Background

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 dependent on fossil fuel may lead to energy crisis and increasing environmental problems such as global warming (Sukiran et al., 2020). To address this issue, renewable energy (RE) was placed as a long-term strategy on the national agenda. The recently launched of the Malaysia Renewable Energy Roadmap (MyRER) 2035 aims to increase RE share in the national power installed capacity to 31% by 2025 with foreseeable reduction in greenhouse gases (GHG) emissions (SEDA, 2022). Renewable resources such as biomass and biogas from the oil palm industry are available in supporting the country's RE development and GHG mitigation action targets.

Malaysia is the world's second largest producer and exporter of palm oil, contributing about 8.5% to the total oils and fats production in 2021 (Parveez et al., 2022). In this process, an abundance of non-oil biomass by-products or wastes is also generated. This includes an approximately 100 million tonnes (t) (wet basis) of biomass in solid and liquid forms, is produced annually from palm oil mills (POMs) alone (Loh et al., 2022). Palm oil mill effluent (POME) is the single largest waste fraction generated from milling process, at an estimated volume about 60 million m^3 annually discharged nationwide (Choong et al., 2018). Due to its high organic content, characterised by a biological oxygen demand (BOD) of 25,000 mg/L and a chemical oxygen demand (COD) of 51,000 mg/L (Bello & Raman, 2017), POME is a major threat to the environment if discharged untreated or inefficiently treated. Conventional anaerobic digestion (AD) for POME treatment via open digester system releases biogas to atmosphere that affecting a sustainable palm oil production.

One of the strategies to address these is to simultaneously treat and reutilise POME for various resource recovery such as biofuel, biogas, biochemical, enzymes, animal feed and biofertiliser (Chia et al., 2020). Among these, biogas is readily available resource from business-as-usual (BAU) scenario of the conventional AD for POME treatment. Therefore, biogas provides significant advantages, compared to other biofuels or products from POME. Capturing biogas using closed anaerobic digester is becoming acceptable practice as an integrated treatment of POME and biogas energy recovery for GHG reduction (Loh et al., 2017). Economic and environmental benefits and potential of biogas capture from POME are widely available in the literature. POMs equipped with biogas plant generate lower GHG 196 kg CO_2eq/t crude palm oil (CPO), compared to 814 CO_2eq/t CPO from conventional mill (Lim & Biswas, 2019). 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. Loh et al. (2017) estimated that the potential CH_4 and electricity generation from biogas in palm oil mills nationwide in 2015 was 726,028 t and 480 MW, respectively.

The first commercial biogas plant deployed in the Malaysian POMs was in early 1980s (Tong & Lee, 2012). In 2020, 130 mills were equipped with biogas plant (Loh et al., 2022). Typical uses of biogas are for heat and power for onsite or offsite utilisation. Recently, production of bio-compressed natural gas (Bio-CNG) or biomethane from POME emerges as an alternative to typical biogas utilization in Malaysia. Upgraded biogas in Bio-CNG form is a natural gas like fuel which can be easily transported and potentially used as fuel in a wide, effective and variety of applications. Bio-CNG offers an attractive utilization pathway and better overall efficiency, economic and environmental benefits compared to conventional uses and biofuel (Pöschl et al., 2010a).

As current scenario of the palm oil industry focuses on sustainable development and income maximization, thus the current status, roles and contribution of biogas production and utilization from POME to achieve these aspirations need to be reassessed and strategized. Evaluation of biogas potential from POME for Bio-CNG production is important as part of initiative to diversify and maximize biogas uses as fuel and increase new biogas capture facilities in POMs.

1.2 Problem Statement and Research Questions

One of the major challenges in producing sustainable palm oil is to treat POME efficiently to reduce emission of methane (CH_4), a GHG that has huge global warming potential. The conventional POME treatment system via open ponding or tank of AD is a challenging process and regarded as a regulatory obligation cost without economic returns. The process also has the lowest potential to exploit the biogas for RE utilisation and GHG reduction. Biogas emission is the highest impact on the environment from palm oil mills which contributed to about 50% of the total GHG emissions from CPO production (Krishnan et al., 2017). For more accurate and representative reporting, an actual status and potential of biogas production and utilization need to be determined based on total biogas plant operated in palm oil mills.

Development of biogas plant in the Malaysian palm oil mills is relatively low with only 28% adoption rate out of 452 mills in year 2020 (Loh et al., 2022). 50 mills utilized biogas for electricity generation and more critically, > 50% of mills with biogas plant merely flare the biogas (Loh et al., 2017). Limited onsite utilization in palm oil mills and the Feed-in Tariff (FiT) quota availability for grid-connection are major reasons for lower biogas uptake and causing the majority of the plants merely flare the biogas. Palm oil mills are self-sufficient in energy that is generated from oil palm biomass-based combined heat and power (CHP) plant. The established offsite utilization via grid-connected electricity under FiT is much dependent on quota availability, which is also very limited and highly competitive through e-bidding process. To overcome this, diversifying its uses in this area is deemed relevant.

Upgrading raw biogas to natural gas quality, i.e., biomethane or Bio-CNG is one of the options to increase and expand biogas utilization, in particular for offsite applications. Study on Bio-CNG production from a large-scale biogas upgrading plant in a palm oil mill is limited and relatively new. As an emerging technology in Malaysia, it is important to further evaluate potential development of Bio-CNG from POME as a benchmark to commercial biogas utilisation.

The following research questions are addressed with regards to biogas and Bio-CNG production from POME:

1. What is the status of POME generation and its use for biogas generation?
2. What is the status of biogas utilisation in Malaysia?
3. How to convert biogas into Bio-CNG in a palm oil mill?
4. What are the technical, economic, and environmental benefits of Bio-CNG produced from POME?

1.3 Aim and Objectives

The aim of the study is to develop a sustainable solution for POME utilization through biogas production, capture, treatment and utilization. Based on the problem statement and research questions, two main objectives are identified as follows:

1. To determine biogas production from POME and its utilisation in Malaysia from overall scenario (all palm oil mills) and mills installed with biogas plant.

2. To evaluate technical, economic, and environmental performance of commercial scale bio-CNG production plant for biogas in a selected palm oil mill.

1.4 Scope of the Study

The study focused on analysis of biogas potential from POME for renewable energy utilisation and Bio-CNG production. Therefore, the scopes of the study are as follows:

1. The analysis provided using data of palm oil mills nationwide from 2019 to 2021.
2. The case study was carried out at a project site (a palm oil mill) where actual production data and samples were collected and analysed pertaining to Bio-CNG production.

1.5 Significance of the Study

The analysis could be used as a basis for the palm oil mill operators and RE developers to adapt the development of biogas and Bio-CNG plants in their respective mills.

1.6 Outline of the thesis

The thesis follows the conventional format with 5 chapters. Overall ideas of the study include research background, problem statement, objectives, novelty and applications, methodology and thesis outline are presented in Chapter 1. Chapter 2 focuses on comprehensive literature reviews of the study, including POME generation, characteristics and its treatment methods, potential of POME as feedstock for various applications e.g., resource recovery and biogas generation. Technical, economic and environmental performance of POME-based biogas utilizations and Bio-CNG production were discussed in this chapter.

Project approach and methodology used to reassess current status of biogas production and utilisation potential, and to evaluate commercial development of Bio-CNG production from POME were described in Chapter 3. Additionally, methods to characterise POME, biogas and Bio-CNG were also included. Chapter 4 presents and discusses results obtained from the study. The findings mainly on availability of POME and biogas, and its potential contribution for various RE generation and GHG savings either for palm oil industry or the country, as a whole. Findings on technical, economic and environmental evaluation of Bio-CNG production in a palm oil mill were presented and discussed. Chapter 5 summarises and concludes major results and findings based on the research objectives. Several recommendations were also highlighted in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Energy is one of the major natural resources playing a crucial role for mankind activities. The world's primary energy resources are mainly from fossil-based and non-renewables. RE is an alternative to reduce high dependency on fossil fuel and its environmental impacts. Currently, RE contributes about 14% to the primary energy supply worldwide where about 70% of the RE sources are from biomass (Popp et al., 2020). The mass production or generation of RE for commercial uses requires huge and continuous supply of feedstocks. One such potential feedstock is biomass including biogas generated from the palm oil industry.

Palm oil is the major commodity in the global oil and fats industry, contributing significantly to the socio-economic of producing countries, including Malaysia. The Malaysian palm oil industry has progressed over 100 years and currently, oil palm is the largest planted commodity crop in the country covering of 5.74 million hectares (ha) nationwide (Parveez et al., 2022). As the world's second largest producer and exporter of palm oil, the country produced 18.12 million t CPO from processing of 90.53 million t FFB in 451 POMs nationwide in 2021 (Parveez et al., 2022). The country's palm oil constitutes about 24% and 8.5% to the global production of palm oil (76.39 million t) and oils and fats (241.36 million t) respectively, in 2021.

Despite its huge market success, the palm oil industry faces numerous issues and challenges, in particular on a sustainable palm oil production. This includes a vast amount of by-products or wastes generated along its supply chain, mainly during harvesting and processing stage at the plantations and palm oil mills. Non-oil biomass represents about 90% of the palms, compared to only 10% of oils. It is estimated that more than 100 million t (wet basis) of oil palm solid biomass and 60 million t of liquid biomass are generated annually from pruning, replanting and milling activities (Loh, 2017; Sukiran et al., 2020). Due to this, the palm oil industry has been established as the country's major industry that generates and utilises renewables resources for energy recovery, particularly generated from POMs. Many opportunities still exist in exploiting the palm oil milling wastes as renewable fuel, especially the biogas from POME.

POME is the single largest waste portion generated from POMs which currently underutilised. Due to its high volume and organic content, POME is regarded as a major source of the environment issues from POMs, affecting sustainable palm oil production. This is mainly attributed by its highly polluting properties and release of biogas to atmosphere during AD of POME treatment. In order to minimise its environmental impacts and create economic value of POME, several solutions have been initiated at various levels of development. This includes to treat and reuse POME simultaneously for various resource recovery and applications, as well as to reduce and eliminate POME. Among these, capturing of biogas from POME for energy recovery has been extensively promoted for economic and environmental sustainability benefits of the industry.

Biogas capture from POME provides significant environmental benefits in cushioning energy security and global warming issues compared to other existing approaches. Several biogas utilisation pathways have been commercially applied with varying level of economic returns. Therefore, it is essential to reassess the potential and current status of biogas capture and utilisation from POME in order to optimise and diversify biogas uses for more effective and wider commercial applications. Upgrading biogas to Bio-CNG or biomethane is an emerging option to the millers, particularly for offsite utilisation.

2.2 Generation of Palm Oil Mill Effluent (POME)

The wet milling process is a typical method to extract CPO and palm kernel from FFB. Figures 2.1 and 2.2 illustrate a brief milling process comprising 4 major subsequent processes or stations; i) sterilisation ii) pressing iii) oil clarification and iv) kernel recovery. The process begins with sterilization of FFB, followed by stripping of the sterilized bunches to separate the fruits and the stalks. At the press station, the fruits are mashed and then pressed using digester and screw press, respectively. The process extracts the crude oil and detaches the nuts from mesocarp fibres. The crude oil is screened, clarified, purified and dried at oil room station to produce CPO. The nuts are separated from pressed cake and cracked prior to kernel-shell separation and drying for kernel recovery.

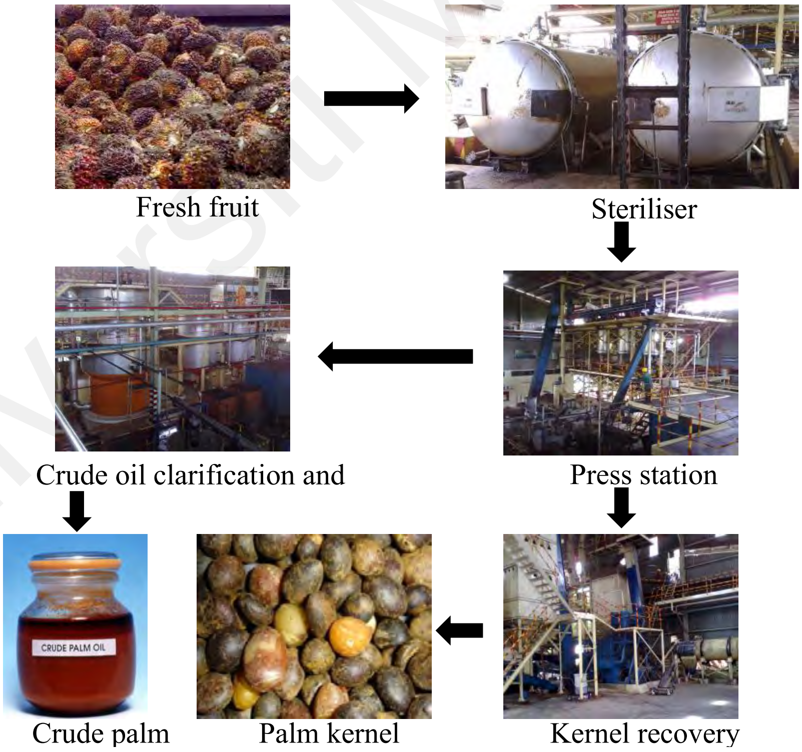

Figure 2.1: Major process and main products from palm oil mills

As a water intensive process, the typical water consumption in palm oil mill ranges from 1.0 to 1.2 m^3/t FFB processed (Kospa et al., 2017). Sources of water are generally from nearby rivers and tube well, which require in-house treatment prior to be used in the milling process. The water is primarily used as feedwater for boiler to produce steam for electricity generation and process heating, as well as for direct use in diluting crude oil during the clarification process and in the wet separation of kernel and shell. Dilution is a major contributing factor to water consumption in POMs, which requires 50% more water than mills without dilution (Subramaniam et al., 2014). As dilution is commonly practiced, thus it contributes to high water consumption and POME generation in POMs.

More than 50% of the water used for milling process are discharged as POME (Loh et al., 2013). The remaining 50% turn out as used water for processing and losses through boiler steam blowdown, evaporation, wash water and leakages (Liew et al., 2015). Subramaniam et al. (2014) reported that an average of 46 – 64% of POME generated from total feedwater used in milling process. Figure 2.2 also illustrates major sources of POME generation in palm oil mills. POME is a mixture of wastewater generated from clarification process (sludge), sterilisation (condensate) and kernel recovery station (hydrocyclone or claybath waste), in 60%, 36% and 4% composition, respectively to total volume of POME (Liew et al., 2015). Other minor wastewater sources in palm oil mills are from mill and machineries cleaning, overflows from vacuum dryer, boiler and back pressure wastes (Patel, 2015). Mills generate an average of 0.65 m^3 POME/t FFB processed (Akhbari et al., 2020). Approximately 60 million m^3 of POME are generated annually nationwide. From the reviewed literature, POME generation depends on various factors including amount of FFB processed and water usage, and method used for milling process.

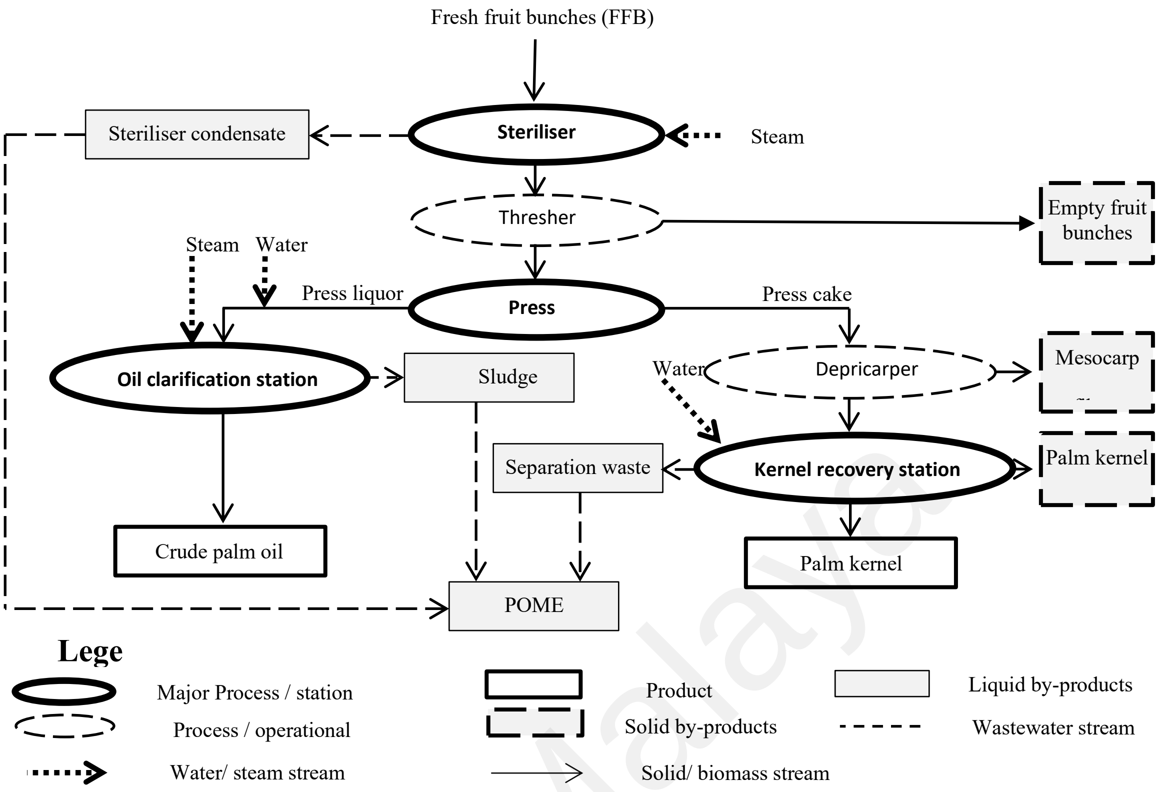

Figure 2.2: Simplified palm oil milling process with major products and by-products or wastes generation

2.3 Characteristics of POME

Physically, the raw POME discharged from palm oil mills is thick brownish viscous acidic liquid with low pH about 4.5, relatively hot at 80°- 90°C, high in colloidal suspension with an unpleasant odour (Patel, 2015). It is composed of 95% water, 4% total organic solids (including suspended solids) and 1% oil and grease (O&G) (Lam & Lee, 2011). Table 2.1 summarises the characteristics of POME generated from the Malaysian POMs. POME is recognised as a rich organic carbon wastewater with high amounts of biological oxygen demand (BOD) (25,000 mg/L), chemical oxygen demand (COD) (51,000 mg/L), O&G (6,000 mg/L) and suspended solid (SS) (18,000 mg/L) (Bello & Raman, 2017). These values categorise POME as high strength wastewater exhibiting its highly polluting characteristics and nutrient-rich resource (Loh et al., 2013). Although non-toxic as no chemical is used during milling process, it is extremely harmful to the environment, particularly to the waterways due to high oxygen depletion if discharge untreated.

Table 2.1: Characteristics of palm oil mill effluent (POME) and discharge limits (Bello & Raman, 2017)

Parameter, mg/L except for pH, temperature, color and toxicity.	Mean value	Limit for discharge [1]
Temperature °C	85	45
pH	4.2	5.0 – 9.0
Biological oxygen demand	25000	100 (50, 20)[2]
Chemical oxygen demand	51000	-[4]
Total solid	40000	-[4]
Total suspended solid	18000	400
Total volatile solid	34000	-[4]
Oil and grease	6000	50
Ammonical nitrogen	35 (4-80)	150
Total nitrogen	750	200
Color (ADMI)	> 500	-[4]
Total organic content[3]	24100 (18600-34600)	-[4]
Total Kjehldahl nitrogen[3]	930 (750 – 900)	-[4]
Volatile fatty acid[3]	1800 (471-3540)	-[4]
Sulfate content[3]	5 (2-8)	-[4]
Lignin[3]	1700 (1600-1740)	-[4]
Toxicity (%)[3]	-42 (-62.1 - -13.3)	-[4]

[1]Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulation 1977, [2]Applicable to sensitive areas, [3]Poh et al. (2010), -[4]Not regulated

Table 2.1 also shows that the regulated parameters and limits on discharged POME set by the Malaysian Department of Environment (DOE) are very stringent and much lower than the raw POME. This indicates that the Government is committed to curb the high pollution potential of POME for environmental protection and sustainability of the industry. Table 2.2 shows characteristics of each wastewater source of POME. Among these, the clarification wastewater contains the highest values of the studied parameters, except for dissolved solid, thus making it the biggest source of organic matters in POME. This is attributed by high unrecoverable oil in clarification wastewater. Combination of these sources significantly contribute to fluctuating characteristics of POME (Liew et al., 2015). Other contributing factors are oil extraction methods, climate and condition of the processing days, cropping season and quality of the FFB (Poh et al., 2010).

Table 2.2: Characteristics of each wastewater sources in palm oil mills (Ahmed et al., 2015)

Parameter, mg/L except for pH	Steriliser condensate	Clarification wastewater	Hydrocyclone wastewater
Chemical oxygen demand	47,000	64,000	15,000
Biochemical oxygen demand	23,000	29,000	5000
Dissolved solid	34,000	22,000	100
Suspended solid	5000	23,000	7000
Total nitrogen	500	1200	100
Ammoniacal nitrogen	20	40	-
Oil and grease	4,000	7000	300
pH	5.0	4.5	-

*-: data unavailable

Table 2.3: Proximate compositions of palm oil mill effluent (POME)

Major constituents, %	Value
Crude protein	7.5[a]
Total lipid	0.36[b]
Ash	4.72[a]
Carbohydrate	9.7[c]
Nitrogen-free extract	40.66[a]

[a]Agida et al. (2019), [b]Iwuagwu and Ugwuanyi (2014), [c]Teh et al. (2017)

Table 2.4: Major and minor traces elements of palm oil mill effluent (POME)

Element	Agida et al. (2019)	Loh et al. (2013)	Ahmad et al. (2011)	Ohimain et al. (2012)
Nitrogen (N), %	-	0.06	3.9	≤0.002
Potassium (K),%	0.37	0.12	2.0	≤0.003
Magnesium (Mg),%	0.25	0.03	0.9	-
Calcium (Ca), %	0.19	0.03	1.6	-
Phosphorus (P), %	0.38	0.01	1.2	-
Iron (Fe), %	0.02	0.01	1.9	≤0.001
Zinc (Zn), mg/l	26.66	1.98	158	-

Table 2.4: Continued

Element	**Agida et al. (2019)**	**Loh et al. (2013)**	**Ahmad et al. (2011)**	**Ohimain et al. (2012)**
Manganese (Mn), mg/l	8.12	2.8	550	-
Copper (Cu), mg/l	3.43	0.85	243	0.61-1.61
Cadmium (Cd), mg/L	-	-	ND	0.004-0.023
Chromium (Cr), mg/L	-	-	23	0.61-1.67
Plumbum (Pb), mg/L	-	-	ND	-
Nickel (Ni), mg/L	-	-	ND	-

*ND: not detectable, - : data unavailable

Tables 2.3 and 2.4 show that POME contains carbohydrates, nitrogen compounds including protein and amino-acids, lipids, dissolved organic nutrients and mineral constituents, making it suitable for biotechnological means and various resource recovery (Wu et al., 2009). This also provides a conducive environment and sufficient resources for microorganism growth for biogas production via AD. POME is safe to be used as it either does not contain toxic heavy metals (Pb, Cd and Cr) or contains it in a very low concentration. However, high biodegradable POME is impossible to be directly used or disposed without appropriate treatment such as biological degradation, enzymatic hydrolysis, phytoremediation and physicochemical treatment (Wu et al., 2009). For disposal purposes, biological method is commonly applied for POME treatment in palm oil mills.

2.4 Conventional POME Treatment System

POME has to be treated before discharging into waterways or for land application within discharge limits as regulated by the Department of Environment (DOE) under the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulation 1977. The conventional POME treatment is primarily based on the biological method of AD using open ponding or tanks system (Loh et al., 2015). AD is recognised as a cost-effective method and capable to treat such a high strength-organic loading POME up to 95% of BOD reduction efficiency (Poh et al., 2010). Ponding system is the most commonly deployed treatment method with 85% adoption rate in POMs. The selection is mainly due to its simplicity in terms of design, operation and maintenance, low capital expenditure (CAPEX) and operational expenditure (OPEX), as well as the location of most of the mills near to the plantations; hence easier for land irrigation or application (Lam & Lee, 2011).

Figure 2.3 illustrates a typical configuration of POME treatment system either using a series of ponds or combined ponds and tanks system. The system involves a few processing stages of physical and biological methods in typical sequences of cooling, mixing, anaerobic, facultative and aerobic or algae ponds. POME is pretreated in deoiling ponds or sludge pit to recover oil, and to remove sand and dirt before entering treatment plant. Raw POME is stabilised to lower temperature and pH of mesophilic condition, typically < 40°C and pH 6.5 – 7.5, in cooling and mixing ponds. AD of POME occurs in oxygen-free condition where most of the organic matters are degraded to CH_4, CO_2 and water, and biogas is emitted to the atmosphere. Anaerobically-treated POME is overflowed to the facultative pond and followed by aerobic ponds, where the remaining organic matters are further degraded with presence of oxygen before discharge. Aerators are also used if necessary.

The conventional treatment is associated with inconsistent treatment efficiency, long hydraulic retention time (HRT) and larger footprint (Loh et al., 2013). To address these, high rate anaerobic bioreactor technologies with potential of biogas capture such as up-flow anaerobic sludge blanket (UASB) and continuous stirred tank reactor (CSTR) (Poh et al., 2010) were studied. These technologies still require subsequent aerobic processes such as extended aeration and tertiary or polishing plant, to consistently comply with discharging limits, particularly in sensitive areas with more stringent limits such as BOD 50 or 20 ppm (Poh et al., 2010). The common polishing plant technologies used in palm oil mills are based on advanced oxidation processes, membrane separation, adsorption and coagulation methods (Bello & Raman, 2017). These are high in CAPEX and OPEX and still incapable for consistent and continuous performance to comply required limits (Liew et al., 2015).

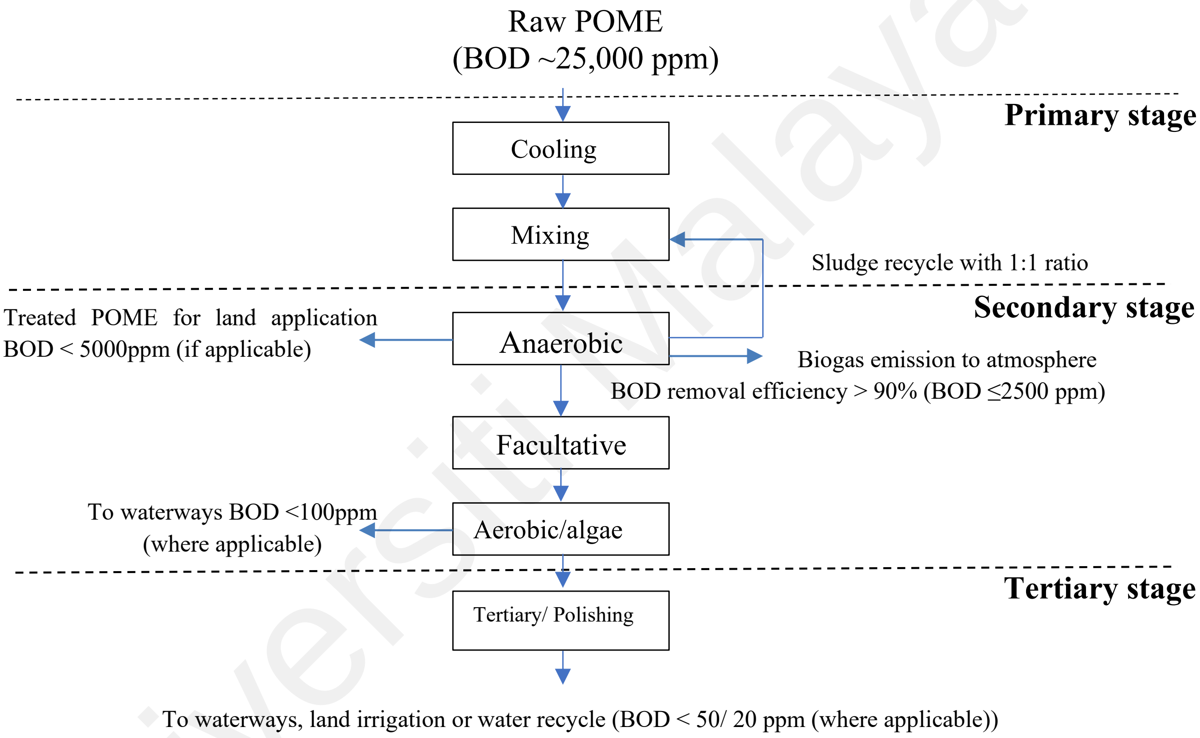

Figure 2.3: Conventional palm oil mill effluent (POME) treatment plant in palm oil mill (MPOB, 2020)

The conventional method poses several operational challenges resulted in poor treatment and emission of odorous and corrosive biogas to the atmosphere. As naturally-occurred process which solely relies on sensitive microorganisms such as *Bacillus*, *Pseudomonas*, *Aspergillus niger* and *Penicillium* (Ohimain et al., 2013) for degradation process, it requires continuous monitoring and maintenance for effective treatment. Operational challenges are mainly attributed by highly fluctuating and variation POME load and characteristics due to seasonal change, weather and process conditions. In addition, AD process depends on various operating parameters such as pH and temperature. These affect bacteria activity, treatment efficiency and stability, formation of scum and sludge resulting in silted ponds problem. Potential energy from biogas is wasted and not recovered, and more critically uncaptured biogas containing GHG that contribute to global warming, a major threat to the sustainable palm oil production. The conventional POME treatment system is also regarded as a regulatory-environmental obligation cost without economic returns to the millers.

2.5 Resource Recovery Potential from POME

One of the strategies to address issues related to conventional POME treatment is to simultaneously treat and utilise POME sustainably for various resource recovery and applications. This can be carried out either via biotechnological advances (Wu et al., 2009) or as by-products from business-as-usual of existing POME treatment. Direct utilisations or applications of POME from the existing AD is for RE via biogas production and as feedstock for liquid and solid-based biofertiliser. Besides, valorisation of POME has successfully produced various types of biofuels such as biohydrogen, biodiesel, biocrude oil (Chia et al., 2020), and bioethanol (Alam et al., 2009), animal feed for pigs and poultry (Zahari & Alimon, 2005), fish and aquaculture industry (Vairappan & Yen, 2008), organic fertiliser and composting (Yoshizaki et al., 2013), biochemical and enzymes (Chia et al., 2020). Recently, treating POME with microalgae is an emerging alternative to conventional treatment which also produces various type of biofuels and biochemical (Low et al., 2021).

Most of these products and processes are on R&D or pilot plant scale, except for biogas and biofertiliser. Theirs commercial potential are limited due to low yield, high CAPEX and OPEX as advanced biotechnologies are required. Issues on technical and product yield require more time and resources to resolve, thus its commercial production may not materialise in the near future. The products still need to be further tested and market acceptance remains unclear, thus it may not be able to compete in terms of pricing and quality with conventional products. The reviewed literature indicated that reusing of POME for biogas is a low-hanging fruit for cleaner production and circular economy approach in generating RE and POME treatment simultaneously. Recovery of biogas in CH_4 and CO_2 forms, is a tool for GHG mitigations, thus enhances the sustainability performance of palm oil.

2.6 Biogas Production from POME

Biogas is a major and readily available valuable by-product generated from AD of POME. AD digests and converts organic material in POME into biogas by two different metabolic routes: mesophilic (35°C) and thermophilic (55°C) conditions. Thermophilic AD was superior to mesophilic conditions in COD removal and biogas production (Jeong et al., 2014). Biogas production under these conditions occurs by acetic acid dismutation and H_2 reduction process of anaerobic methanogenic archea, respectively (Garritano et al., 2018). Table 2.5 shows the metabolic reactions during AD involves a sequence of four important stages, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis (Demirel & Scherer, 2008; Kavuma, 2013).

Table 2.5: Biochemical process of anaerobic digestion and methane production

Stage	Metabolic	Bacteria	Metabolite
1 Hydrolysis	Complexorganics, proteins, lipids and carbohydrates	Extracellular enzymes	Soluble fatty acids, alcohols, CO_2 & NH_3
2 Acidogenesis	Soluble fatty acids, alcohols, CO_2 & NH_3	Acidogenic bacteria or Acid formers	Volatile fatty acids,VFA (acetic, propionic butyric acids),alcohols, aldehydes,H_2, CO_2
3 Acetogenesis	VFA	Acetogenic bacteria	Acetate, H_2 and CO_2
4 Methanogenesis	Acetate	Acetotrophic methanogens	CH_4 and CO_2
	H_2	Hydrogenotrohic methanogens	CH_4

Source: (Aziz et al., 2020; Bala et al., 2014; Garritano et al., 2018; Gerardi, 2003; Ohimain & Izah, 2017; Schink, 1997)

The first step of the AD involves the hydrolysis of organic compounds into smaller units, such as sugar and amino acid. In the next step, acidogenic bacteria breaks down the hydrolysis products into organic acids, mainly acetic acids, H_2 and CO_2. Acid phase products is converted into acetate, H_2 and CO_2 via acetogenesis reaction (Bajpai, 2017). Methanogenesis is a final stage of AD where acetate and hydrogen are converted to CH_4 and CO_2 using acetotropic and hydrogenotrophic bacteria, with CH_4 generation ratio by these bacteria pathways is 70:30 (Kumaran et al., 2016).

Biogas production is influenced by the environmental and internal factors. Environmental factors are mainly temperature and pH, which determine the performance of the internal working condition of the biogas technology. Internal factors refer to conditions that influence biogas production in anaerobic configuration such as mixing, nutrients, organic loading rates, HRT, microbial population and activities, presence of inhibitory materials, pressure and chemical equilibrium (Ohimain & Izah, 2017).

2.6.1 Characteristics and Potential of Biogas from POME

Physically, biogas is colorless, odorless and lighter than air. Biogas and CH_4 yields generated from the AD of POME are commonly reported in the 28 m^3 biogas/m^3 POME (Muzzammil & Loh, 2020) and 0.25 kg CH_4/kg COD removed (Chin et al., 2013), respectively. Biogas comprises of 60 – 70% CH_4, 30 – 40% CO_2 and 800 – 1500 ppm H_2S (Loh et al., 2013). CH_4 is the only combustible gas in biogas, where higher CH_4 represents better quality of biogas generation (Chia et al., 2020). H_2S is unwanted element causing adverse effects to the ecosystem such as odours, corrosiveness, acid rain and living health. The CV of biogas containing 55 -75% CH_4 is typically between 22-30 MJ/

Nm^3 (higher heating value) and 19 – 26 MJ/Nm^3 (low heating value) (De Mes et al., 2003).

With a calorific value of 20 MJ/m^3, 1 m^3 biogas could generate 2.78 kWh (Subramaniam et al., 2021), thus providing good energy content as a renewable fuel. The methane emission rate from the ponds is 6.54 kg/t FFB, corresponding to 137.4 kg CO_2 eq. (Schuchardt et al., 2008). A review by Garcia-Nunez et al. (2016) indicated that CH_4 emission was 46 m^3/t CPO. Energy potential from 578,693 t CH_4 generated from POME is equivalent to 823 million L diesel or 402 MW installed capacity of biogas plant in 2011 (Chin et al., 2013). Loh et al. (2017) reported that 1776 million m^3 biogas containing 726,028 t CH_4 was generated from 63.42 million m^3 POME with potential of biogas power plant installed capacity of 480 MW. Recently, 510,000 t of CH_4 were generated from 58.5 million t of POME in 2018 (Chia et al., 2020), which is equivalent to 8.72 kg CH_4/t POME. The conventional anaerobic-open ponding or tank is not feasible in producing a higher biogas yield, including to capture and utilise generated CH_4 for energy recovery (Loh et al., 2013). A closed anaerobic digester is a direct, cost-effective and environmentally friendly alternative to POME treatment while tapping the biogas.

2.6.2 Anaerobic Bioreactor Technology for Biogas Production from POME

POME treatment system equipped with biogas capture facilities gains a lot of attention to compliment the non-profitable conventional POME treatment alone. Table 2.6 summarises high-rate bioreactor technologies for anaerobic digestion of POME treatment and biogas production. It can be seen that commonly studied POME bioreactor technologies in the past 15 years were UASB, up-flow anaerobic sludge-fixed film (UASFF), CSTR, expanded granular sludge bed (EGSB), membrane anaerobic system (MAS) and integrated anaerobic,-aerobic bioreactor (IAAB). The reviews concluded that due to more advanced control and process system, many improved high-rate AD bioreactors had been developed or modified from the conventional high-rate AD throughout the years. As controlled and monitored process, these technologies improve treatment efficiency and quality treated POME, resulted in increased biogas yield in the shorter HRT and smaller footprint. The major disadvantages of these systems are the high CAPEX, OPEX and required skilled workers to operate the relatively advanced process (Chia et al., 2020).

A few of these technologies were successfully scaled up and tested at pilot plant. The results of pilot plant studies of IAAB (Chan et al., 2020), anaerobic expanded granular sludge bed (AnEG) (Tabassum et al., 2015) and CSTR (Irvan et al., 2018) have correlated well to bench-scale findings. Only CSTR and UASB are the most common technologies deployed for commercial operation. CSTR is known for its simplicity in terms of design, operation and enhanced mixing rate (Mahmod et al., 2020). Similarly to UASB technology, its major advantages including producing high quality effluent and CH_4 yield (Poh & Chong, 2009).

Table 2.6: Anaerobic bioreactor technologies of palm oil mill effluent (POME) treatment for biogas production

Reactor type	**Conditions**	**HRT (days)**	**Methane generation rate (L CH_4/g COD removed) (unless stated)**	**COD removal efficiency, %**	**Reference**
Up-flow anaerobic sludge-fixed film (UASFF)	Mesophilic 38 °C	1.5	0.34	97.0	Zinatizadeh et al. (2006)
UASFF	Mesophilic 38 °C	3	0.35	97.0	Najafpour et al. (2006)
Single-stage	Mesophilic 37–42 °C	17	0.15	97.0	Yacob et al. (2006)

Table 2.6: Continued

Reactor type	Conditions	HRT (days)	Methane generation rate (L CH_4/g COD removed) (unless stated)	COD removal efficiency, %	Reference
Continuous stirred tank reactor (CSTR)	Mesophilic 37 °C	7	0.30	71.0	Choorit and Wisarnwan (2007)
CSTR	Thermophilic 55 °C	5	0.27	70.0	Choorit and Wisarnwan (2007)
Expanded granular sludge bed (EGSB)	Mesophilic 35 °C	2	8.05 kg COD/ m^3.d	91.0	Zhang et al. (2008)
CSTR	Thermophilic 55 °C	6	- (64% CH_4)	90.0	Poh and Chong (2010)
UASB	Thermophilic 55 °C	5	0.45	95.5	Fang et al. (2011)
EGSB	Thermophilic 55 °C	5	0.42	95.0	Fang et al. (2011)
Membrane anaerobic system (MAS)	Mesophilic 35°C	6.8	0.25 – 0.57	98.4	Abdurahman et al. (2011)
Integrated anaerobic, aerobic bioreactor (IAAB)	Mesophilic 27- 29°C	14	0.32	99.0	Chan et al. (2012)
Anaerobic hybrid reactor (AHR)	Mesophilic 37 °C	-	0.17-0.27	93.5	Choi et al. (2013)
Suspended closed anaerobic bioreactor (SCABR)	Mesophilic 37 °C	12	0.046	87.0	Wong et al. (2013)
Ultrasonic-assisted membrane anaerobic system (UAMAS)	Mesophilic 35°C	4	0.26 – 0.47	98.7	Abdurahman and Azhari (2013)
UASB-hollow centered packed bed (UASB-HCPB)	Thermophilic 54°C	2	60% CH_4	90.0	Poh and Chong (2014)

Table 2.6: Continued

Reactor type	**Conditions**	**HRT (days)**	**Methane generation rate (L CH_4/g COD removed) (unless stated)**	**COD removal efficiency, %**	**Reference**
Carrier anaerobic baffled reactor (CABR)	Mesophilic 35 °C	26	0.25	80.0	Malakahmad and Yee (2014)
High-rate CSTR	Thermophilic 54°C	3	0.27	82.0	Khemkhao et al. (2015)
Anaerobic expanded granular sludge bed (AnEG)	Mesophilic 34 °C	-	(30 m^3/m^3 POME – 57% CH_4)	94.0	Tabassum et al. (2015)
Integrated ultrasonic membrane anaerobic system (IUMAS)	Mesophilic 35°C	9	0.7	98.0	Abdurahman et al. (2017)
CSTR	Thermophilic 55°C	6	0.8	82.0	Irvan et al. (2018)
Thermophilic anaerobic membrane bioreactor (TAnMBR)	Thermophilic 55°C	-	0.56	98.0	Yee et al. (2019)
Two-stage UASFF	Thermophilic 54°C	1	0.8	66.0	Zainal et al. (2020)
CSTR	Thermophilic 55°C	2	0.26	85.0	Mahmod et al. (2020)
IAAB	Mesophilic 35 - 40°C	10	0.26	99.0	Chan et al. (2020)

*-: information unavailable

2.6.3 Industrial-Scale Biogas Plant Technology in Palm Oil Mills

A commercial biogas capture technology used in palm oil mills is mainly based on a closed digester tank and covered lagoon system, which deployed CSTR and UASB technology, respectively. As of 2016, 50 mills installed closed digester tanks and another

36 mills used covered lagoons to capture the biogas from AD of POME treatment nationwide (Loh et al., 2017). A closed digester tank is a preferred technology due to its proven track record of operation and maintenance reliability, higher biogas yield, smaller footprint and shorter HRT, though the CAPEX and OPEX are much higher than covered lagoon technology. A study reported that highest CH_4 production from closed digester tank was 0.23 kg CH_4/kg COD treated, compared to only 0.16 kg CH_4/kg COD removed obtained from the covered lagoon technology (Chin et al., 2013). Lower efficiency of the conventional covered lagoon system, mainly due to lack of process control and long HRT Table 2.7 summarises commercial biogas technologies for POME treatment in Malaysia.

Table 2.7: Summary of commercial technologies for biogas capture from anaerobic digestion of palm oil mill effluent (POME) treatment

Technology provider	Digester type / material	Working principle/ condition	HRT, days	Biogas generation, m^3/ m^3 POME	COD mg/L (ex-digester)	Reference
Novaviro – Keck Seng	Tank / mild steel	CSTR / mesophilic	17.5	28	8000 – 12000	Tong et al. (2016)
MPOB – Biogas Environmental Engineering	Tank / concrete	High efficiency fermentation / mesophilic	9	26 – 30	1400 – 2500	Loh et al. (2016)
Green & Smart	Tank / mild steel coated with cold tar epoxy paint	Mesophilic	14	24	5000	Subbiah and Ahmad (2010)
MPOB-Ronser- SJU	Tank/ carbon steel	AnEG / Mesophilic	9	28	< 2800	Loh et al. (2017)
Biotec International Asia	Covered lagoon / geo-membrane	UASB / Mesophilic	27	25 m^3/t FFB	-	Kervyn and Conil (2011)
Green Lagoon Technology	Covered lagoon	In-ground UASB/ Mesophilic	< 40	28 – 32	-	Green Lagoon Technology (2016)

Table 2.7: Continued

Technology provider	**Digester type / material**	**Working principle/ condition**	**HRT, days**	**Biogas generation, m^3/ m^3 POME**	**COD mg/L (ex-digester)**	**Reference**
Cenergi SEA	Covered lagoon/ HDPE	Mesophilic	30	30	4500	Loh et al. (2017)
Kubota Corp.	Tank/ glass-fused-to-steel	AnMBR/ Thermophilic	13	30	-	Lim and Biswas (2019) Lau (2014)

Table 2.6 shows that systems generate an average of 24-32 m^3 biogas/m^3 POME, which is comparable to typical biogas yield of 28 m^3 biogas/ m^3 POME. A typical closed digester tank design comprises both fixed and floating roof as biogas storage. The floating roof system deploys either a flat-top designed or dome shaped roof with a single or double membrane is used as a gas holder, which helps to stabilize the flow and regulates the biogas produced. These tanks are mainly constructed from mild steel and reinforced concrete. Advanced materials such as fusion-bonded epoxy, glass-fused to steel tank and stainless steel bolted are now used to construct the tanks.

A covered lagoon digester uses either a sealed cover high-density polyethylene (HDPE) geo-membrane or linear low density polyethylene (LLDPE) by installing it over the existing or newly constructed anaerobic ponds to create a closed AD system (Chin et al., 2013). The membrane is sealed by means of strip-to-strip welding and a peripheral anchor trench dug around the perimeter of the pond. A basic covered lagoon system was first introduced during the Clean Development Mechanism (CDM) programme. Foong

Lee Sawiminyak Sdn. Bhd. located in Sg. Siput, Perak is among the pioneer mills adopted a covered lagoon biogas system in Malaysia.

In recent years, the covered lagoon design has improved significantly, particularly in multiple feeding and desludging systems, and mixing mechanism via biogas and hydraulic mode (Yap et al., 2020). These resulted in higher biogas yield which is much similar to digester tank, and lesser HRT compared to basic system. The covered lagoon system also achieved COD removal efficiencies of >85% within 22-30 HRT. Due to its larger volume, covered lagoon system is suitable for higher capacity mills with huge land availability.

Reviewed literature shows that biogas technologies for POME are established and progressively improved towards higher yield and treatment efficiency. Most of the information on these technologies were reported by the technology providers, thus need to be further assessed from the long terms - commercial operation points of view.

2.7 Utilisation Pathway and Business Model of Biogas from POME

The use of captured biogas for energy generation is mainly driven by a need to tap its energy potential for economic benefits either on the local demands, cost savings or from various incentives offered by the Government. RE potential from biogas can be commercially exploited via various utilisation pathway or business model, which is primary based on heat, power or both (combined heat and power) generation either directly or in upgraded form of biogas (Figure 2.3).

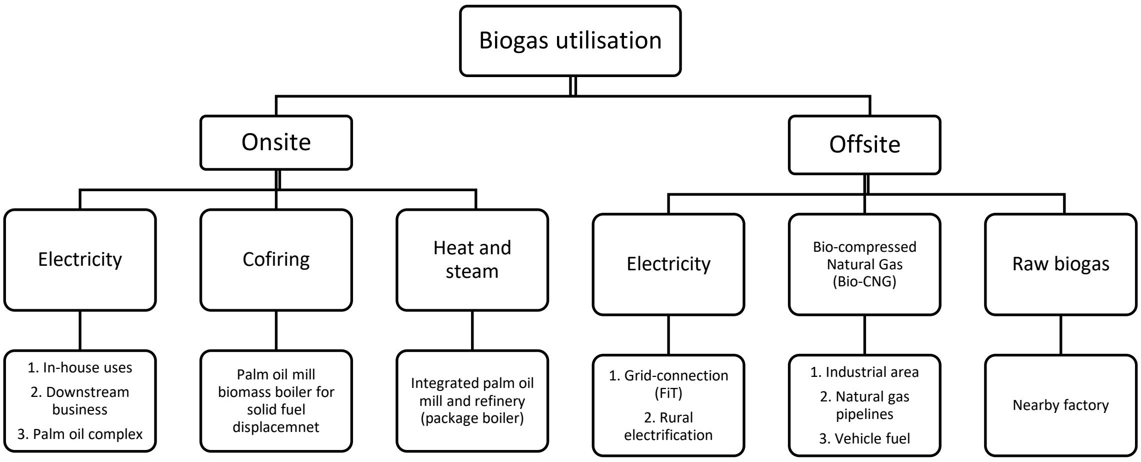

Figure 2.4: Utilisation and business model potential of biogas from palm oil mill effluent

Biogas could be used for both onsite and offsite utilisations creating additional revenues from the sale of energy generated and/or saving on the operational cost of the mill, if it is internally used. Typical onsite biogas utilisation in palm oil mills via electricity generation and biogas cofiring. Figure 2.4 shows the basic process and system for electricity generation from biogas comprises of closed digester, biogas scrubber, chiller dyer and gas engine. Raw biogas is treated to remove H_2S to an acceptable level of gas engine, typically < 200 ppm (Firdaus et al., 2017). Biological scrubber is often used compared to chemical scrubber, due to its environmental friendly and more economical process. Treated biogas from scrubber is dried using chiller dryer prior to electricity generation using internal combustion engine or gas engine with electrical efficiencies in the range of 38 – 42% (Firdaus et al., 2017). Other technologies used to generate electricity are diesel generator via cofiring, micro gas turbine and fuel cell, which are seldom used in the country.

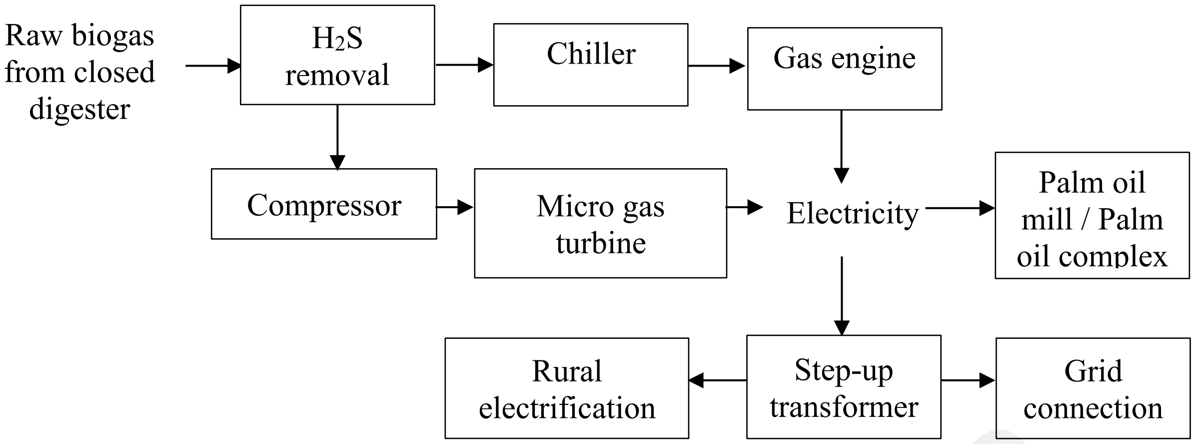

Figure 2.5: Electricity generation for onsite and offsite applications

Electricity generation is a feasible option for mills and integrated palm oil complex comprises of mill and plantations which require additional energy and to support potential downstream activities and businesses. Biogas cofiring in biomass boiler is an immediate and direct biogas utilisation that can be deployed in palm oil mills (Figure 2.5). Major advantage of biogas cofiring is it displaces oil palm biomass used as boiler fuel, mainly palm kernel shells (PKS) which can be sold as a feedstock for value-added products. Displacement of biomass facilitates in particulate emission reduction from the boiler chimney. Raw biogas can also be sold to nearby industries that require fuel for heat generation. This has been commercially demonstrated by supplying biogas to a brick factory which improved the sustainability criteria and revenues of the mill (Lim & Biswas, 2019). Biogas can be used in a package boiler or chiller operated in the refinery that integrated with POMs (Loh et al., 2017). A significant saving in fuel and electricity cost is achievable via this approach.

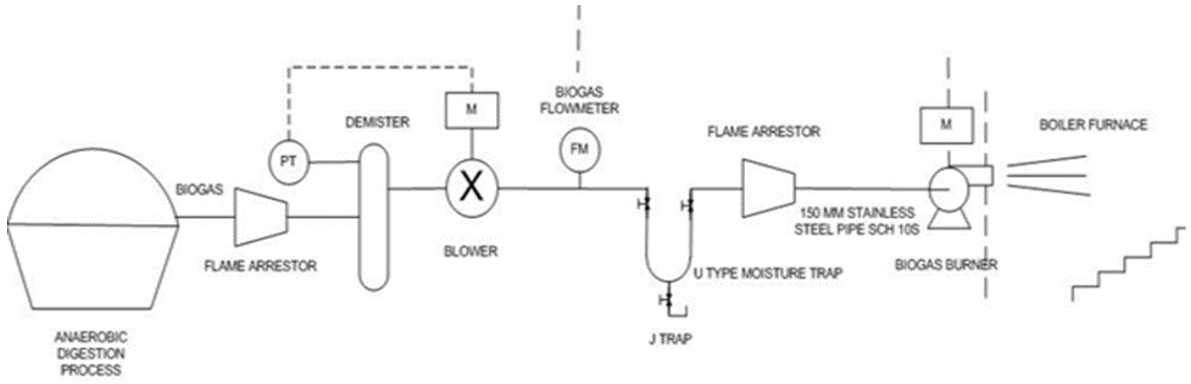

Figure 2.6: Biogas – biomass cofired system operated in palm oil mill boiler

Exporting electricity to the national grid via FiT programme is an established and proven business approach for biogas plant in the country. In total, 30 biogas plants were connected to the national grid in 2019 (Loh et al., 2019b). Mills with grid-connected electricity supply or in the vicinity of the sub-stations may have an advantage, provided that the interconnection point is not overloaded with RE connection and with available load demand. Biogas plant for local grid via rural electrification is another feasible offsite approach to those mills surrounded by housing or settlement areas that depends on diesel-based power for electricity. This approach would reduce fuel cost and utility bill of the settlers in the sustainable manner.

From reviewed literature, the commercially typical uses of biogas for heat and power generation are limited either for internal uses in POMs or offsite applications, mainly via FiT programme. This is due to self-sufficient energy from oil palm biomass in POMs and limited FiT quota which has resulted in low biogas plant development in POMs nationwide. In total, 125 mills or 28% of total POMs have installed biogas plant in 2019 (Loh et al., 2019b) . For comparison, Indonesia, the largest palm oil producing countries had less than 10% mills installed with biogas plant from >850 mills in 2020. The potential for energy generation from all POME in Indonesian mills to reach 1.1 GW. However, only 130 MW of potential capacity is currently installed in 2020 (Setiawan et al., 2022)In addition, Recently, upgrading biogas for Bio-CNG or biomethane production has been identified as a potential option to increase and diversify the use of biogas in the country, particularly for offsite applications. The major methods and technologies for biogas upgrading to Bio-CNG are described briefly in the following section.

2.8 Upgrading Biogas for Bio-Compressed Natural Gas (Bio-CNG) Production

Biogas upgrading system is an emerging technology option in the country to increase, optimise and diversify the use and marketability of biogas from POME. Biogas in the upgraded form is easily transported and potentially used in effective, wider and variety applications (Hakawati et al., 2017). The process improves and upgrades raw biogas to high quality fuel either in compressed or liquefied biogas, syngas or advanced liquefied biofuel via various upgrading pathway (Figure 2.6). A basic-typical biogas upgrading system produces a natural gas quality fuel, known as biomethane or Bio-CNG. Biomethane or raw biogas can be further processed to produce bio-liquid natural gas (Bio-LNG) via liquefaction process and combined cryogenic-liquified process, respectively (Baccioli et al., 2018). Liquid biofuel such as gasoline, diesel and jet fuel can also be produced from biomethane via reforming and followed by Fisher-Tropsch synthesis (Kadam & Panwar, 2017).

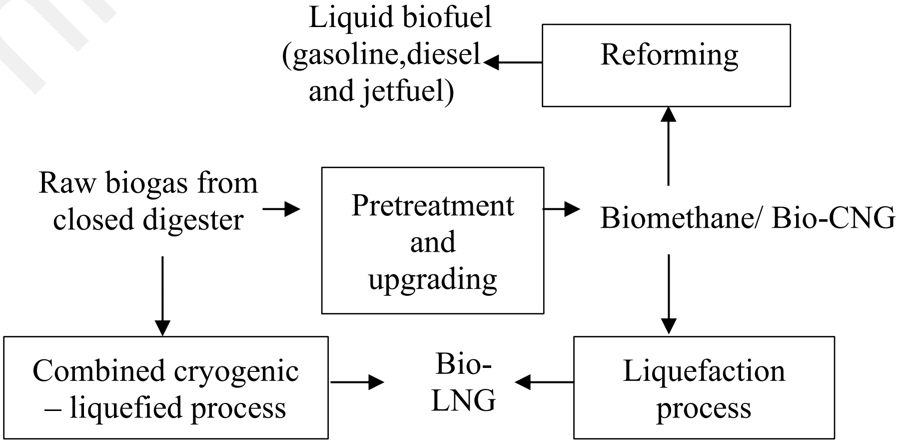

Figure 2.7: Overview of biogas upgrading for bio-compressed natural gas (Bio-CNG) production and other potential biofuels

Biogas upgrading for biomethane or Bio-CNG production is currently the most common route deployed for commercial exploitation. The process aims to produce a comparable gaseous fuel quality to natural gas, in term of gas composition and properties. It has been commercially implemented in some developed countries since the early 80's or 90's where Europe is the world's leading of biomethane production (Scarlat et al., 2018; Wellinger, 2013; Wellinger et al., 2013). According to European Biogas Association, as of 2015, 459 biogas upgrading plant were in operation in Europe producing about 1231 million m^3 biomethane, where Germany was a leader with 185 biogas upgrading plants (Scarlat et al., 2018). In total 340 Bio-CNG plants injected in to the pipelines and another 697 filling stations were set up across Europe for vehicle use.

The process to upgrade raw biogas to natural gas quality involves multi-stage procedures by primarily removal of unwanted-pollutant gaseous and trace elements in raw biogas such as CO_2, H_2S and water using physical, chemical and biological methods (Noyola et al., 2006; Ryckebosch et al., 2011). This increases CH_4 content in biogas to more than 90% in the final product, resulted in increase of energy content and meeting the Wobbe Index specification. The final product composition is also based on the required specifications depending on the various applications and end users. Table 2.8 shows biogas properties for natural gas pipelines injection set by some countries. The final product of Bio-CNG for pipelines injection typically contains >90% CH_4, <6% CO_2, <5% O_2 and <45 mg/m^3 sulphur.

Table 2.8: Major biogas quality requirements for natural gas pipelines injection of selected countries (Salihu & Alam, 2015)

Parameter	Germany	Denmark	Austria	Sweden	Switzerland	Netherland	France
Wobbe index, MJ/Nm^3	37.8-46.8	51.9-54.9	47.9-56.5	45.4-48.6	47.9-56.5	43.46-44.41	43.3-46.8
CH_4,%	87-98.5	87-91	>96	95-99	>50	>80	-
CO_2, %	<6	1.4	≤2	≤3	<6	-	<2
O_2, %	<3	-	≤5	<1	<0.5	-	-
H_2, %	≤5	-	≤4		<5	<12	<6
Total sulphur, mg/m^3	30	-	10	23	30	45	30

In general, the production of Bio-CNG from biogas in a palm oil mill involves the following major-subsequent steps: 1) pretreatment (H_2S and water (H_2O) removal), 2) purification and upgrading (CO_2 removal and CH_4 enrichment) and 3) gas compression and storage. Several ways and methods of removing the H_2S, H_2O and CO_2 in biogas from POME are commercially available and described in the following section.

Bio-CNG for onsite applications may not feasible, mainly due to sufficient energy from oil palm biomass and limited energy required in POMs. Therefore, it is a potential option for the mills that are not feasible for grid connection or nearby to the natural gas pipelines or industrial areas without natural gas supply. Due to its versatility and flexibility, Bio-CNG can be compressed for storage, transported and distributed to end users via mobile pipeline (trailer) and injected to natural gas pipeline. As a direct natural gas substitute, Bio-CNG is used for heat and power generation or both as well as for vehicle fuel.

2.8.1 Technical Evaluation of Upgrading Biogas to Bio-CNG

The technical performance of biogas upgrading typically evaluates the system performance from energy efficiency perspective of production and utilisation of the upgraded biogas. Biogas upgrading to biomethane and its applications represent an attractive utilization pathway based on Primary Energy Input to Output (PEIO) (Pöschl et al., 2010b). It has higher overall efficiency and superior economic analysis compared to the electricity generation. Although most of biogas are used for combined heat and power (CHP) but their electrical efficiency is limited and can be less than 40% if the heat was not exploited (Walla & Schneeberger, 2008; Zuccari et al., 2015). Therefore, a new frontier for energetic exploitation of the biogas is currently by biogas upgrading to biomethane (Micale, 2015).

A direct use of biogas has the highest efficiency with limited market and applications, meanwhile energy efficiency of upgraded biogas was comparable to other biogas utilization due to its advantages such as ease of transport and diversified market uses. (Hakawati et al., 2017). A comparative evaluation on compressed and liquefied biogas by Gustafsson et al. (2020) showed that there were no significant different on the technologies used. The study also indicated that liquefaction process is a good option for biogas distribution for long distance. A comparative study on biogas for electricity and biomethane production concluded that energy balance of the plant depends on the biomethane production and excess production resulted in the plant was dependent to external energy (Caposciutti et al., 2020). In addition, production of 1 MJ biogas required 2.5 MJ energy input, compared to natural gas which is just slightly higher than 1 MJ (Jury et al., 2010).

The reviewed literature indicated that biogas upgrading is a potential approach to improve overall efficiency and widening market access of biogas uses. Despite the growing interests, there is still substantial lack of study in this area of Bio-CNG production from POME.

2.8.2 Removal Technologies of Hydrogen Sulphide from Biogas

H_2S comprises on average of 2000 ppm in the raw biogas of POME, is generated from sulphate reduction in wastewater (Angelidaki et al., 2018). Due to its corrosive nature, H_2S removal is the first treatment stage required for any upgrading process as well as for utilisation purposes. The presence of high H_2S affects the upgrading plant components and quality requirement of upgraded biogas for end-user applications. There are several methods for desulphurisation process with various H_2S removal efficiencies, which can be done during the digestion process (in the digester) and after the digester. A direct H_2S removal in the anaerobic digester occurs when metal iron such as iron chloride or air/O_2 is dosed during AD to form an insoluble metal sulphide or elementary sulphur, respectively (Ryckebosch et al., 2011). These methods are inefficient for high-end biomethane quality applications.

H_2S removal methods after digester are based on physical (adsorption, absorption and dilution), chemical (absorption, adsorption, neutralisation and combustion) and biological (activated sludge and biofilter) and membrane technology (Promnuan & Sompong, 2017; Zulkefli et al., 2016). Physical absorption involves absorbing H_2S in water or organic solvent where water scrubbing technique is commonly used. Chemical absorption occurs by dissolving H_2S in liquid phase and followed by chemical reaction using chemicals such as NaOH and $FeCl_3$. H_2S pretreatment of biogas generated from POME-EFB co-digestion using chelate-iron process achieved 99% of removal efficiencies (Park, 2021). Zulkefli et al. (2016) concluded that chemical absorption is much effective process compared to physical route.

The adsorption process for H_2S removal penetrates and adsorbs into pores solid of adsorbent. Major adsorption technologies are using iron oxide or hydroxide, activated carbon and pressure swing adsorption (PSA). POME-biogas treated with ferric oxide reduced about 80% of H_2S concentration from inlet value (Muzzammil & Loh, 2020). Activated carbon is mostly used and studied adsorbent, mainly due to its technical performance and cost–effective process. Via membrane, unwanted H_2S is permeated through thin membrane and the enriched CH_4 is retained (Ryckebosch et al., 2011).

Although highly efficient, major disadvantages of chemical and physical methods as well as membrane are attributed by high OPEX and pollutant generation (Promnuan & Sompong, 2017). Absorption process is also a challenging and difficult technique (Ryckebosch et al., 2011). Biological method via technologies such as biofilter and bioscrubber has lower CAPEX and OPEX with good removal efficiencies. This gas-liquid separation process absorbs H_2S in the liquid phase and oxidised by specific bacteria to sulphur biologically with addition of air or O_2. Promnuan and Sompong (2017) reported that the technology reduced H_2S in biogas from POME with 80% of removal efficiency. Since biogas upgrading is required to produce ultra-low H_2S level gaseous fuel similarly to natural gas, the selection of suitable methods must be tailored-suited with the raw biogas characteristics, process efficiencies, operation cost and final product specifications.

From the reviewed literature, H_2S removal technologies can be divided into two main categories, 1) good removal efficiency (with limited certain maximum level) and low cost, and 2) high efficiency with high cost. For cost-effective process, desulphurisation process can be done by stages with a combined method. Basically 2 major steps involve, namely primary stage to reduce the raw H_2S level to certain level using inexpensive biological method. The 2nd stage involves a fine-tuning process in which to further reduce the biologically treated H_2S to ultra-low level according to end-user requirements via high-end technologies such as activated carbon. This cost–effective approach also facilitates to prolong the lifespan of the activated carbon.

2.8.3 Removal Technologies of Water

Biogas generated from wastewater sources, such as POME is saturated with water vapour, H_2O, derived from medium evaporation at concentration of 0 - 10% (Angelidaki et al., 2018; Kadam & Panwar, 2017). H_2O presence in biogas is also due to H_2S pre-treatment methods used such as biological or water scrubber. Removal of water is necessary in order to avoid potential corrosions of internal parts of the upgrading system, piping and energy conversion technologies. H_2O level limits are also required for pipeline injection and vehicle use. The H_2O can be removed via physical and chemical (adsorption and absorption) drying methods, and refrigerator (Kadam & Panwar, 2017). A chiller dryer is a common technology used to drying the biogas in palm oil mill biogas power plant and upgrading plant. The H_2O will be further reduced simultaneously with ultra-low level desulphurisation process, prior to compression of biogas for CO_2 removal.

2.8.4 Removal Technologies of Carbon Dioxide

During the biogas upgrading and purifying stage, the CO_2 is removed, thus increasing the CH_4 concentration and its calorific value (Starr et al., 2012). Since the biogas upgrading technologies are derived from natural gas separation technologies, thus the commercially available technologies to date were developed based on the 4 major following methods: 1) adsorption, 2) absorption, 3) membrane permeation and 4) cryogenic (Makaruk et al., 2010; Ryckebosch et al., 2011).

Adsorption methods involves CO_2 adsorption on solid surface of the adsorbents under specific conditions and trapped by the size of the molecular sieves (Salihu & Alam, 2015). The pressure swing adsorption (PSA) using carbon molecular sieves is the most common adsorption-based method used for commercial applications. Other adsorbents that can be used are zeolite and activated carbon. Absorption is defined as dissolution of gas or vapour into the liquid phase. Removal of CO_2 via absorption method can be performed via physical and chemical absorption using scrubber unit. Physical absorption uses water (water scrubber technology) and organic solvents such as polyethylene glycol (Singhal et al., 2017). Chemical absorption deploy organic solvent, typically amine. Both adsorption and absorption methods are also capable of removing other unwanted compounds carried over from the previous pretreatment i.e. O_2, N_2, H_2S, H_2O simultaneously (Angelidaki et al., 2018; Ryckebosch et al., 2011).

In the recent development, membrane and cryogenic are 2 major commercial technologies developed based on separation principle for CO_2 removal. The polymer semi-permeable type membrane technology is regularly used which the off-gas or permeate is CO_2 (and H_2S) CH_4-rich gas is the product gas. A cellulosic spiral wound membrane used for CO_2 removal in biogas from POME-EFB enabled to achieve 94% efficiencies (Park, 2021). Unlike absorption and adsorption methods, membrane is limited in terms of trace elements removal. Thus, raw biogas as a feeding gas required to be pretreated to dry and ultra-low level H_2S for efficient separation and to extent its lifespan. The cryogenic is the latest commercial and highly advanced technology developed for biogas upgrading, in particularly for Bio-LNG production (Adnan et al., 2019). Raw biogas can used directly to the system with less or no specific pretreatment unit required, due to capability of the system to remove unwanted trace element during the process (Baccioli et al., 2018). Biological method is being investigated for CO_2

removal. Due to high specification of gas quality and consistency, its application is not yet suitable for commercial scale (Ryckebosch et al., 2011).

From reviewed literature, the upgrading yield using various CO_2 removal technologies is 65 -68%, whereas membrane technology has lowest methane purity of 91% compared to more than 97% efficiencies via other technologies (Khan et al., 2017). Similarly to H_2S removal technologies, technology selection mainly depends on plant capacity (feedstock and Bio-CNG production), end-product quality, type of utilisation or application, and economic parameters of the technology (CAPEX, OPEX, lifespan etc.).

2.9 Economic Analysis of Biogas and Bio-CNG from POME

Economic evaluation of biogas from POME is widely available and often conducted on biogas utilisation potential for electricity generation. Development of biogas power plant is more economically viable in a 60 t/h mill capacity and above, due to economic of scale (Shahida & Saad, 2013). A 30 t/h mill installed with biogas plant had internal rate of return (IRR) and payback period (PBP) of 12.5% and 6.6 years (Gozan et al., 2018). 1.9 MW grid-connected biogas plant developed in a 60 t/h mill has more attractive IRR and shorter PBP of 29.7% and 3.7 years only (Foong et al., 2020). Larger capacity biogas plant contributes to lower CAPEX and OPEX for every MW, thus generates more electricity and profit compared to smaller capacity plant.

An integrated biogas and composting plant offers better economic performance with 21% IRR within 4 years PBP, compared to stand alone approach (Yoshizaki et al., 2013). An additional revenue from carbon trading increased IRR and shorten the PBP significantly to 32% and 2.9 years. Biogas plant with fertiliser and carbon credit revenues offered IRR and PBP of 14.3% and 4.66 years, respectively (Lok et al., 2020). Biogas cofiring in biomass boiler, where palm kernel shell is displaced and sold, offers highest economic return compared to electricity generation, cooking gas and flaring, based on a comparative study conducted for 60 t/h mill (Abas et al., 2013).

Recently, several economic evaluations were also conducted on Bio-CNG from POME. Membrane technology has the shortest PBP and most economical option compared to other upgrading technologies for pipeline quality of Bio-CNG (Mohtar et al., 2018). Water scrubber technology provides the highest economic performance for Bio-CNG distribution using trucks (Hong et al., 2021). These indicated that the technology used and distribution options play a significant role for better return. Longer PBP of 10 years for Bio-CNG plant invested in a 60 t/h mill can be improved by 34% reduction in CAPEX, imposing treatment cost to millers, introducing subsidies and CER (Foong et al., 2020). By introducing carbon trading price of RM 80/t CO_2, 227 biogas upgrading plants can be constructed in Peninsular Malaysia with a total bio-CH_4 production of 56 million m^3/year (Hoo et al., 2017). Supply of biogas via virtual pipelines is more feasible option compared to upgraded biogas, mainly due to higher logistic, compression and upgrading cost of upgraded biogas (Lee et al., 2019). A comparative study of integrated biogas upgrading plant with CO_2 utilisation for microalgae using various upgrading technologies resulted in insignificant profit reduction (Lee et al., 2017). Khan et al. (2017) reported that water scrubbing technology has a lowest maintenance cost, followed by membrane separation, PSA and cryogenic.

This reviewed literature indicated that biogas plant for electricity generation is the most economical utilization pathway for POME, particularly for larger mill capacity > 60t/h. Integrated biogas-composting plant and tapping various stream revenues such as sludge (fertilizer) including carbon credit are major strategies to improve economic performance of the biogas plant. Governmental frameworks such as policy, incentives and infrastructure are required to make Bio-CNG an economically-competitive business.

2.10 Environmental Evaluation of Biogas and Bio-CNG from POME

POME is the major environmental burden of palm oil mills contributing to water, soil and air pollutions including biogas emissions (Hasanudin et al., 2015). Discharging of raw POME into water sources significantly changes its physical-chemical properties, causes oxygen depletion affecting aquatic organism and limited water access for household uses (Iwuagwu & Ugwuanyi, 2014). POME disposes onto soil resulted in soil acidity (pH <6), decreasing in nutrient availability, texture and enzyme activity, thus reduce its fertility (Nmaduka et al., 2018). About 50% of the total GHG emissions from palm oil production is from biogas emissions (Krishnan et al., 2017). Thus, main motivation to capture the biogas is due to its huge environmental benefits with renewable energy potential, if utilised. The potential of GHG savings from POME-based biogas plant was mostly assessed using Life Cycle Assessment (LCA) approach.

Biogas contributed about 896.48 kg CO_2eq/t CPO, corresponding to >90% of the total GHG emissions of 987.18 kg CO_2eq/t CPO in palm oil mills (Subramaniam et al., 2010). Bong et al. (2017) estimated that 17 – 20 million t CO_2eq/year of potential GHG savings could be achieved if all palm oil mills captured biogas generated from POME treatment. Biogas power plant with CSTR technology generated higher GHG emissions of 1429 kg CO_2eq/MW compared to only 1077.67 kg CO_2eq/ MW from covered lagoon technology (Raman et al., 2019). Electricity generation from these biogas systems show a net environmental benefit on global warming (GW) and acidification potentials except a negative impact in terms of eutrophication potential (Sharvini et al., 2020). A cradle-to-gate life cycle environmental of biogas production from POME indicated that the potential impacts were on GW and water consumption which contributes to human health and ecosystem (Aziz & Hanafiah, 2020).

POME treatment integrated with biogas and composting plant is the most environmental friendly option, compared to biogas plant, land application and membrane technology (Nasution et al., 2018). A study by Hasanudin et al. (2015) demonstrated that 25 – 40 kWh of electricity could be generated from biogas for 1 t FFB with GHG emissions reduction about 109 – 175.35 kg/t FFB processed. Recent study reported that GHG savings potential of 13.36 kg CO_2/m^3 biogas if biogas is captured and utilised for electricity with displacement of 2.7 kWh/m^3 biogas of non-renewable energy (Subramaniam et al., 2021).

These reviewed literatures clearly indicated that capturing and utilising biogas as fuel provide two types of GHG savings, namely saving via biogas trapping facilities in preventing GHG emissions to the atmosphere and substitute fossil fuel with captured biogas for energy generation. Nevertheless, the environmental impacts assessment on Bio-CNG production from POME is still lacking. The following section briefly summarises the environmental performance of biogas upgrading from non-POME based biogas worldwide.

2.10.1 Environmental Assessment of non-POME-based Bio-CNG

A comparative study on biogas for electricity and biomethane production showed that an optimal level of biomethane production exists that minimizes the emissions of equivalent CO_2 (Caposciutti et al., 2020). Many researchers concluded that the biogas upgrading is the cleanest option for management of organic fraction of municipal solid waste (Ferella et al., 2019). According to Ravina and Genon (2015), biomethane production is more environmentally sustainable in terms of GHG emissions, reduction of NOx and particulate matter than being used in a combined heat and power unit. Level of greenhouse gases (GHG) of Bio-CNG varies from -36 to 10 g CO_2eq./MJ compared to 72 g CO_2eq/MJ of natural gas (Valli et al., 2017). Therefore, Bio-CNG or biomethane provides a carbon-negative substitute for fossil fuels, which its GHG reduction amounting to 200g CO_2 eq/kWh (Adelt et al., 2011). In transportation sector, 100% Bio-CNG as fuel reduces about 119 g CO_2/kWh (Cucchiella & D'Adamo, 2016). In addition, GHG emissions of vehicle using Bio-CNG is 5g CO_2eq/km compared to 124 g CO_2eq/km using natural gas (Ferella et al., 2019).

Although there are wide applications and advantages of Bio-CNG as a natural gas substitute, the high capital investment, energy demand and operational expenditure are among the drawbacks of biogas upgrading plant for commercialization (Petersson & Wellinger, 2009). The largest environmental impact was contributed by fossil fuel used in the production of Bio-CNG from co-digestion feedstock e.g. manure, silage, whey, corn and grain by-products (Repele et al., 2014). Besides, a study by Starr et al. (2012) shows, a newly developed biogas upgrading technology using a high pressure water scrubber with an improved environmental performance by 34 - 55%.

As a summary, environmental assessment of biogas production and utilisation has a positive impact to climate change, resource and total renewable energy generation. Results obtained depends on the scenarios analysed in the phase of evaluation, technology and feedstock used and biomethane utilisation. As emerging biogas utilisation in the country, the study in these areas, is deemed necessary for commercial Bio-CNG production from POME.

2.11 Research Gaps

Based on the reviewed literature and analysis, several areas can be further assessed in commercial production and utilisation of biogas from POME for nationwide implementation as follows:

2.11.1 Mapping of Palm Oil Mills for Biogas Utilisation

As most of the mills are located in the rural areas (Lee et al., 2019), a mapping of palm oil mills to the nearby interconnection points, the natural gas pipelines, industrial areas and villages without grid electricity is important to assess the actual potential of biogas and identify potential mills for offsite utilisations.

2.11.2 Detailed Commercial Biogas Plant Performance Analysis

Technical performance evaluation of the commercial POME-biogas plant throughout the operation years and optimum-efficient route of biogas utilisation is to be initiated. Study within these areas are still lacking, particularly on covered lagoon technology (Choong et al., 2018) and new biogas uses, such as Bio-CNG.

2.11.3 Evaluation of Emerging Uses of Biogas

Biogas utilisation needs to be diversified and extensively studied, particular for emerging uses. This includes upgrading biogas to Bio-CNG, bio-liquid natural gas (Bio-LNG) and utilization of biomethane for liquid biofuel production such as kerosene and diesel (Neuling & Kaltschmitt, 2018). Recovery of by-products from biogas plant and upgrading plant could improve overall efficiency and economic value of the biogas. For instance, recovered CO_2 from biogas upgrading plant is used for microalgae cultivation for biomolecules extraction (Low et al., 2021).

2.12 Summary of Literature Review

The treatment of POME to achieve discharge limits and to reduce GHG emissions efficiently is still remains a challenge to palm oil mills in achieving sustainable palm oil production. The literature reviews verify the significant role of capturing biogas via closed anaerobic digester for various energy recovery applications. The potential of biogas capture and utilisation from POME was evaluated from technical, economic and environmental performance. The integrated POME treatment and biogas plant has a positive impact to treat and reuse POME effectively which significantly improves sustainability performance and revenue to palm oil mills.

On the basis of the literature review, most of studies related to biogas production from POME aimed to improve biogas yield and treatment efficiency via various process conditions and methods, bioreactor designs and technologies. Techno-economic and environmental assessment of biogas utilisation from POME mainly focused on established route of electricity generation for grid-connection. The potential evaluation of new uses, such as Bio-CNG or biomethane production from POME is still lacking in the country. Diversifying biogas uses, in particular via Bio-CNG is identified as strategic efforts to expedite nationwide biogas implementation. The technology for immediate implementation is commercially available.

The literature review confirms that upgrading biogas provides several advantages, in particular for offsite utilisation in terms of logistics, more effective and wider biogas applications. This will address the logistic issues and limited uses of biogas which has hindered its development in palm oil mill nationwide. Therefore, knowledge of actual potential of biogas from POME for Bio-CNG production is important to exploit of its commercial potential as an emerging alternative to typical biogas utilisation in the country.

CHAPTER 3: METHODOLOGY

3.1 Overall Methodology and Project Approach

This chapter describes the materials, methodology, and project approach used to achieve the objectives of the study. The overall research methodology of the study consists of 2 major elements (Figure 3.1); i) assessment of biogas potential for RE generation and GHG emissions reduction from the Malaysian palm oil mills, and ii) evaluation of potential development of Bio-CNG from POME in a palm oil mill. RE potential of biogas capture from POME was carried out based on overall potential from all mills and mills equipped with biogas plant nationwide. Evaluation of Bio-CNG production from POME involved on-site plant monitoring, data and samples collection and analysis. Data obtained was used to determine technical, economic and environmental performance of Bio-CNG. A 400 m^3/hr biogas upgrading plant installed at a 54 t/hr palm oil mill was used as a basis of this study.

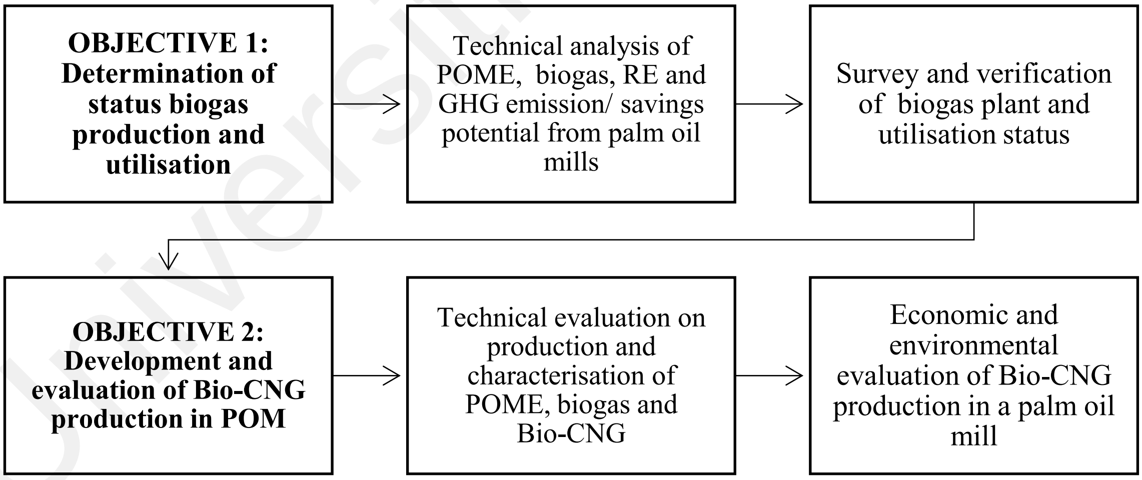

Figure 3.1: Overall methodology and project approach of the research

3.2 Potential Biogas and Renewable Energy from POME

The potential of biogas and RE generation from POME was assessed based on two different scenarios, namely the overall technical potential and the 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 3.1). 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 3.1 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).

Table 3.1: Approved fresh fruit bunches (FFB) capacity and FFB processed of the Malaysian palm oil mills in 2019 -2021

Table 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

[a]FFB processed/approved FFB capacity

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 FFB could produce 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 (3.1) and (3.2) were used to calculate the potential amount of $POME_{volume}$ (m^3) and $Biogas_{volume}$ (m^3) from the FFB processed in POMs (Sarwani et al., 2019).

$$POME_{volume} = 0.65 \times FFB_{processed} \tag{3.1}$$

where 0.65 is the generation rate of POME per t FFB processed (m³/t) (Akhbari et al., 2020) and $FFB_{processed}$ is the amount of FFB processed by the mills (t).

$$Biogas_{volume} = 28 \times POME_{volume} \tag{3.2}$$

where 28 is the production rate of biogas, m³/m³ 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 (3.3) and (3.4) (Loh et al., 2017) as follows:

$$Energy_{potential} = Biogas_{volume} \times CV_{biogas} \tag{3.3}$$

$$Electricity_{potential} = Biogas_{volume}\ X\ CV_{biogas} \times \frac{1}{3600} \times \eta_{gas\ engine} \times \frac{1}{7200} \tag{3.4}$$

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) 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 (Chin et al., 2013) and 35 MJ/m^3 estimated from Lee et al. (2019), respectively using Equations (3.5) and (3.6) which were developed according to Chin et al. (2013):

$$Diesel_{equivalent} = Energy_{potential} \div CV_{diesel} \tag{3.5}$$

$$Natural\ gas_{equivalent} = Energy_{potential} \div CV_{natural\ gas} \tag{3.6}$$

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 (3.7) (Sarwani et al., 2019) as follow:

$$BioCNG_{potential} = 0.6\ X\ Biogas_{volume} \tag{3.7}$$

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).

3.3 Greenhouse Gases Emissions and Potential Savings from Biogas Capture and Utilisation

The amount of GHG emissions from biogas of POME could be determined using the Intergovernmental Panel on Climate Change (IPCC) based on the amount of CH_4 generated, $CH_{4volume}$, as shown in Equation (3.8) (Hasanudin & Haryanto, 2018). This was estimated using the IPCC default value of CH_{4yield}, 0.25 kg CH_4/kg COD removed (Chin et al., 2013) as follows:

$$CH_{4volume} = POME_{volume}\ \times\ COD_{POME}\ \times\ 1000\ (L)\ \times\ CH_{4yield} \tag{3.8}$$

where $CH_{4volume}$ is the amount of CH_4 generated (t) from POME via AD, volume conversion (t to L) of 1000 and COD_{POME} is the mean value of COD for POME, 51000 mg/L (Bello & Raman, 2017).

As the global warming potential of CH_4, GWP_{CH_4}, (based on the IPCC fourth assessment report), is 25 times that of CO_2 (Subramaniam et al., 2021), the associated GHG emissions could be determined using Equation (3.9) (Loh et al. (2017) as follows:

$$GHG_{emissions} = CH_{4volume}\ X\ GWP_{CH_4} \tag{3.9}$$

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 (3.10) (Subramaniam et al., 2021) based on an overall 80% plant efficiency (assumed based on COD removal from POME during AD and also biogas capturing efficiency) as follows:

$$GHG_{savings} = GHG_{emissions} \ X \ 0.8 \tag{3.10}$$

The potential GHG savings ($GHG_{electricity}$, t CO_2eq) made from the use of biogas for electricity generation could be determined using Equation (3.11) 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.

$$GHG_{electricity} = Electricity_{potential} \ X \ 7200 \ X \ \ EF \tag{3.11}$$

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; Sabah and Wilayah Persekutuan Labuan, 0.522 t CO_2/MWhr^{-1} and Sarawak, 0.330 t CO_2 MWhr (MGTC, 2019).

3.4 Status of Biogas Capture and Utilization

Analysis on status of biogas capturing facilities and their utilization approaches in the Malaysian POMs was conducted via a survey using previously collected database in

2021. Table 3.2 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 utilization, installed capacity (MW) and future planning, if any for those biogas plants currently on flaring option. The findings were summarized as number of mills plus percentage biogas utilisation or number of mills plus total installed capacity (MW).

Table 3.2: 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

3.6 Development and Evaluation of Bio-CNG Production in a Palm Oil Mill

3.6.1 Site Information

The study was conducted at a biogas upgrading plant operated in a palm oil mill situated in Selangor. Table 3.3 and Figure 3.2 shows technical and operation design and process flow of the mill. Installed capacity of the mill for FFB processing is 54 t/h with total annual approved FFB throughput is 259,000 t/y. More than 50% of the FFB are supplied from FGV plantations and settlers. The mill deploys a conventional method to process FFB using major operation units such as horizontal steriliser, vertical clarification tank and sludge separator for oil room station, and hydrocyclone unit for kernel recovery. Steam and electricity for mill operation and process heating are generated from biomass-based combined heat and power plant using mainly mesocarp fibres and palm shells.

Diesel genset is used to supply electricity during start-up, shut-down and non-processing hours of the mill.

Table 3.3: Basic operational and technical design of the palm oil mill

Parameter	Description
Location	Kuala Kubu Bahru, Selangor
Year of commissioned	1984
Installed capacity, t/h	54
Approved FFB throughput, t/y	259,000
FFB supply/ source	Own crop: 55%, outside crop: 45%
Source of raw water	Nearby river
Installed capacity of combined heat and power	Steam boiler: Maker/ model: Takuman 600 2 unit x 20 t/h steaming capacity, 21.7 bar Steam turbine 1 unit x 500 kW (KKK) 1 unit x 700 kW (Nadrowski)
Diesel genset	2 unit x 250 kW (Cummins)
Palm oil mill effluent treatment system	Covered lagoon and open ponding system
Final discharge limit	Watercourse discharge BOD 100 mg/L and below

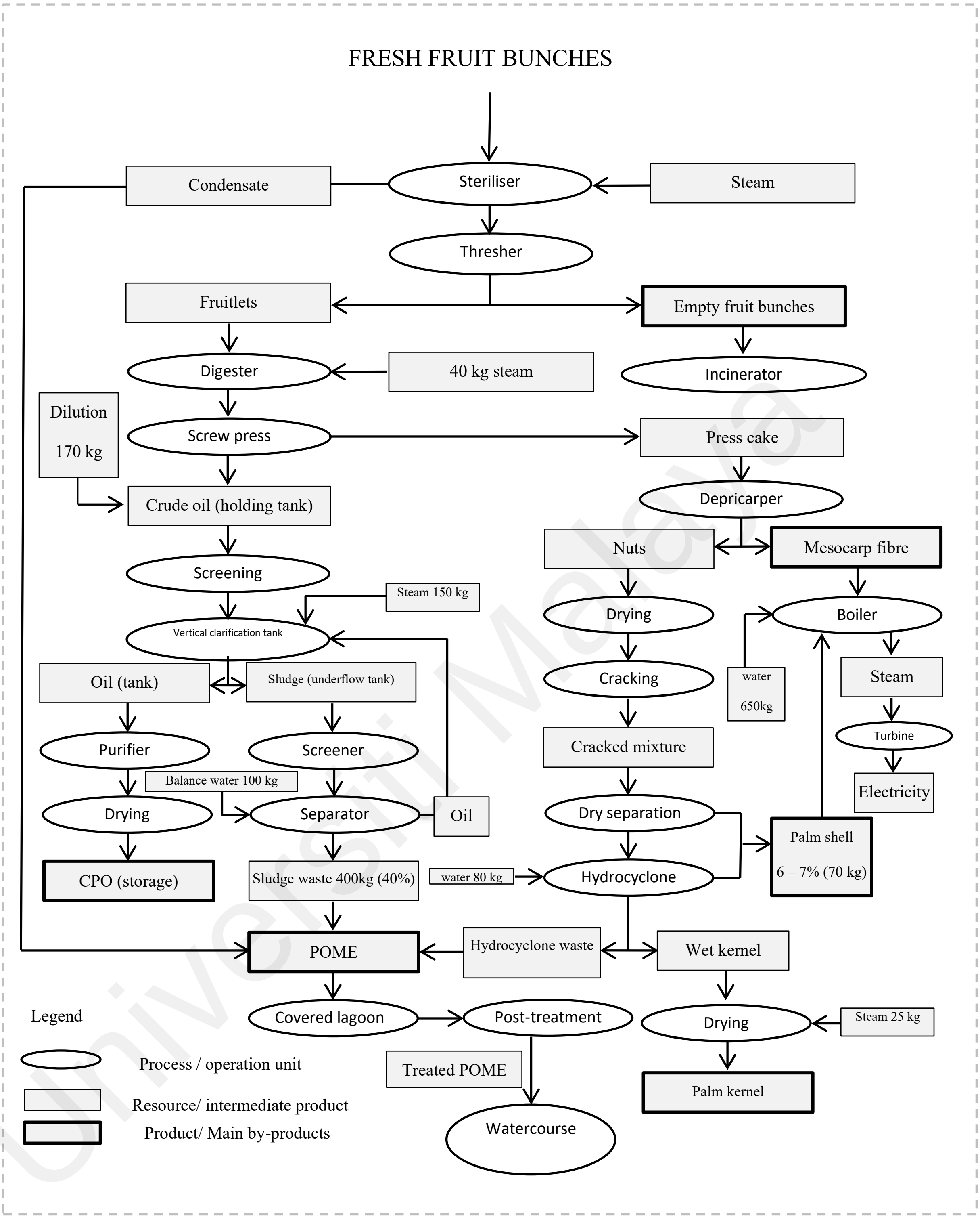

Figure 3.2: Palm oil milling process deployed in the palm oil mill

Figure 3.3 shows the process flow of a conventional ponding system integrated with covered lagoon system deployed by the mill for POME treatment. Raw POME of the mill is a mixture of separator sludge (clarification wastewater), steriliser condensate and hydrocyclone wastewater. Sludge and condensate wastewaters from separator and steriliser are pretreated to recover residual oils and remove dirt, sand and soils, prior to be discharged from the mill to effluent treatment system. The discharged raw POME at 80-90°C from the mill is pumped to the mixing tank 1 and then cooled down to about 40°C using the cooling tower. The raw POME is mixed with the recycled sludge from the covered lagoon for further pH and temperature adjustment prior to be pumped into the closed anaerobic digester via 18-feeding pipes installed along the digester.

The capacity of covered lagoon digester is 42,000 m^3 with designed HRT about 30 days. The feeding pipes were designed to operate on alternate basis to create continuous feeding-mixing effect throughout the digester and anaerobic process. Biogas generated from anaerobic digestion process is captured and stored for Bio-CNG production. The sludge from the end part of the digester is recycled either to mixing tank or the digester to facilitate the mixing and maintain effluent concentration. The anaerobically treated POME is overflowed into a settling pond prior to be pumped into the existing-conventional ponding system of the mill.

The sludge from the settling pond is either recycled to the mixing tank or pumped to sludge ponds for disposal. The process flow of the conventional open ponding treatment system is arranged in series for following subsequent process; mixing ponds – anaerobic ponds – facultative ponds – algae pond. The dimensions of each mixing, anaerobic and facultative pond (in length x width x depth) are 54 m x 54 m x 3.4 m, 76.8 m x 38.7 m x 5 m and 117.6 m x 36.6 m x 4.7 m, respectively. The mill is granted with the DOE license to discharge their treated POME to inland watercourse with BOD limit less than 100 mg/L.

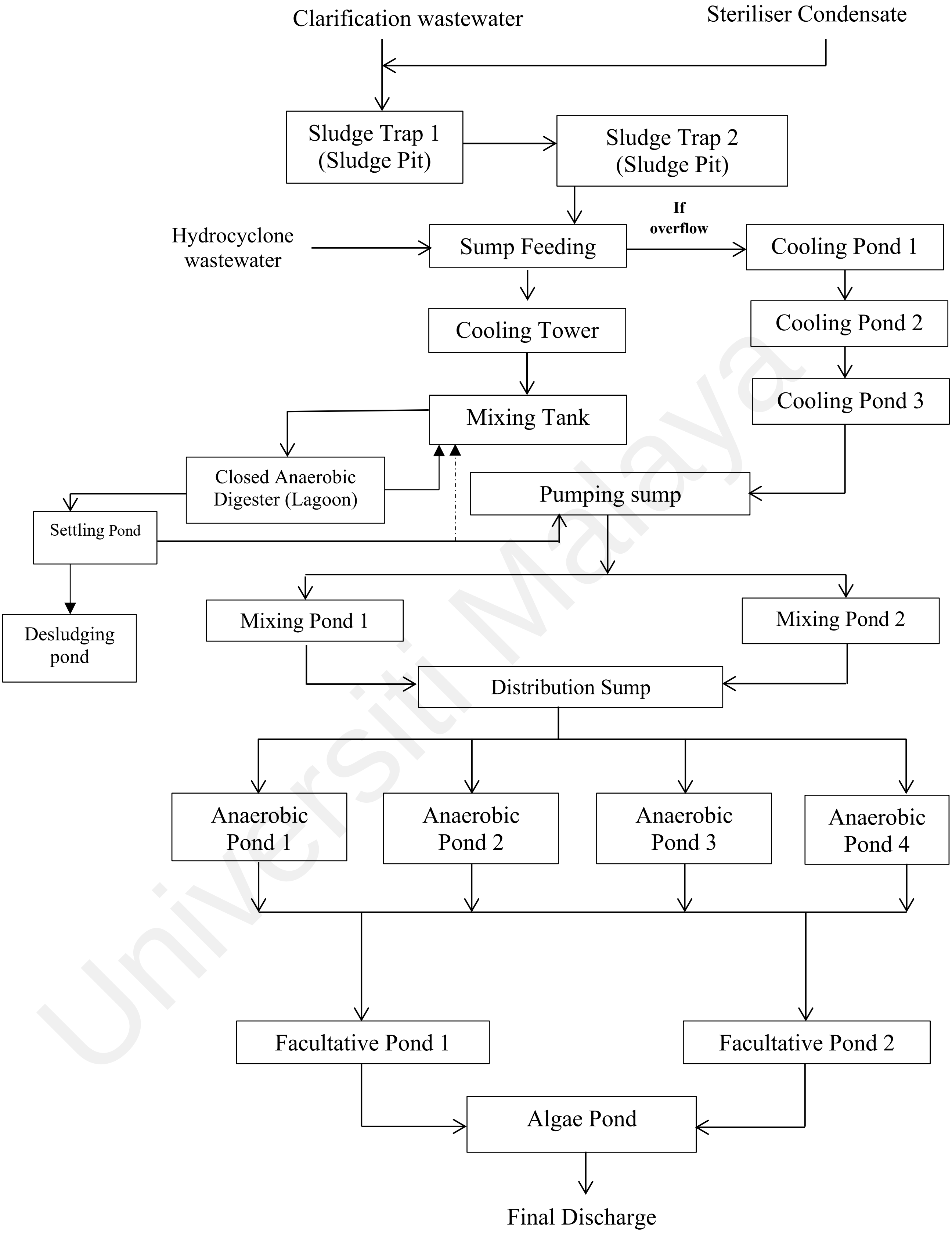

Figure 3.3: A conventional ponding system integrated with covered lagoon system

3.6.2 Renewable Energy Potential from POME of the Mill

Volume of POME, biogas and renewable energy potential of the mill were estimated based on annual approved FFB processing capacity and actual FFB processed for processing year of 2019 to 2021. Equations 3.1 to 3.7 as described in sub-section 3.2 were used to determine annual POME and biogas generation and potential of renewable energy from the mill.

3.6.3 Monitoring of POME Treatment and Biogas Plant Performance

The mill installed a biogas plant using geo membrane-based covered lagoon technology for anaerobic digestion of POME treatment. Performance of the biogas plant was monitored on monthly basis for 6 months duration. The POME samples were collected from inlet (raw POME) and outlet points of covered lagoon biogas plant for analysis. Other samples collected for analysis were separator sludge, steriliser condensate, hydrocyclone wastewater and final discharge of treated POME. The characteristics of POME and the individual samples (steriliser condensate, sludge separator and hydrocyclone) were analysed for BOD, COD, total nitrogen (TN), ammoniacal nitrogen (AN), total solid (TS), total volatile solid (TVS), suspended solid (SS), volatile suspended solid (VSS), volatile fatty acid (VFA) and oil and grease (O&G); based on the revised methods by the DOE, Malaysia approved method (DOE,1995) and the Standard Methods for Examination of Water and Wastewater (APHA, 2005) as described by Loh et al. (2013).

The biogas plant performance and the potential GHG savings could be determined via reduction efficiencies of these parameters using equations 3.12 and 3.13 as below:

$$BOD_{removal\,\%} = \frac{(BOD_{inlet} - BOD_{outlet})}{BOD_{inlet}} \times 100\% \tag{3.12}$$

$$COD_{removal\,\%} = \frac{(COD_{inlet} - COD_{outlet})}{COD_{inlet}} \times 100\% \tag{3.13}$$

The GHG savings potential was calculated using equation 3.8 as described by Hasanudin and Haryanto (2018). Raw POME and sources of POME from the mill were sundried and followed by oven dried to obtain the solid samples for proximate and ultimate analysis. The proximate analysis to determine moisture, ash, volatile matter and fixed carbon contents was carried out using a thermogravimetric analyser (LECO TGA 701) according to ASTM D 5142–90. The gross calorific value (GCV) of the POME samples was determined using a bomb calorimeter (LECO AC 600) in accordance with ASTM D-5865. The ultimate analysis was conducted using LECO CHN 628 and LECO S 628 to determine carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents according to ASTM D5373.

3.6.4 Production of Bio-Compressed Natural Gas (Bio-CNG)

The Bio-CNG plant was completed in December 2014 and commissioned in January 2015 with the objective to demonstrate a techno-economic viability of commercial Bio-CNG production from POME. The plant is located next to the biogas plant and was designed to process 600m^3/hr raw biogas (±10%) or produce approximately 360-400 m^3/hr Bio-CNG. This corresponds to annual Bio-CNG production of 2.46 million m^3 or 80,000 MMBTu. Technical evaluation scope comprises of all operational unit steps that are necessary to upgrade raw biogas to Bio-CNG. Raw biogas from the biogas plant was supplied to the Bio-CNG plant using a blower booster.

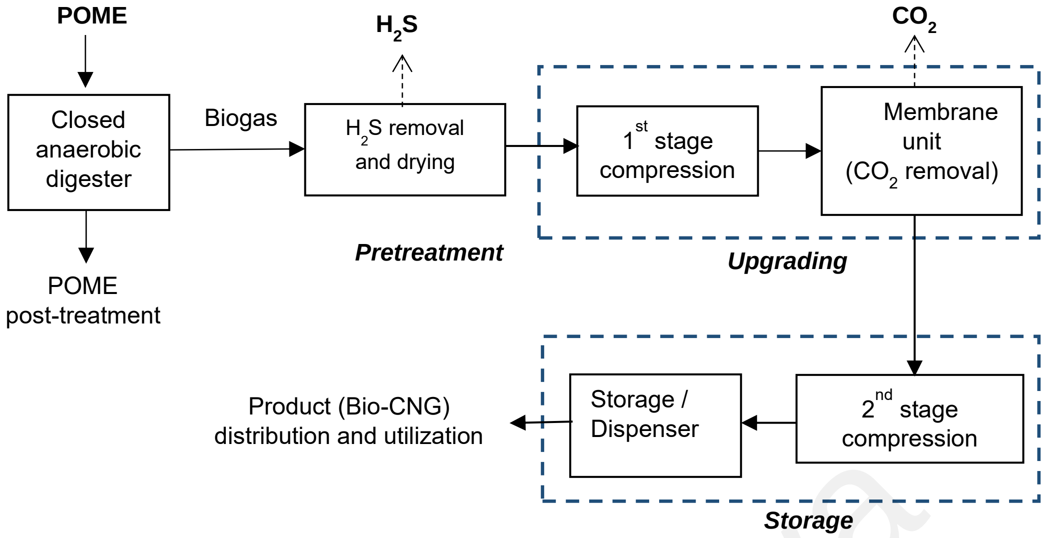

Figure 3.4: Process flow diagram of Bio-CNG production from POME

Bio-CNG plant system comprising the following three subsequent major operations; i) pretreatment, ii) upgrading and purifying, and iii) compression and storage (Figure 3.4). The first stage of the Bio-CNG production involved removal of the H_2S from raw biogas using biological and physical adsorption process, namely biological scrubber (bio-scrubber) and followed by activated carbon. Table 3.4 and 3.5 summarise basic designed parameters of bioscrubber and major operation units of Bio-CNG plant, respectively.

The bioscrubber was primary designed to operate with a conventional air injection using air blower unit. The sulfides removal via biological process is attributed by the activities of sulfur-dioxiding bacteria which air supply is required. Other biological treatment options studied were 1) bioscrubber with pure O_2 injection, and 2) bioscrubber with O_2-enriched air injection. Figures 3.5 and 3.6 illustrate the process flow of H_2S removal system and O_2-enriched air production for biological process. The O_2 content in purified air generated from air purification system was approximately > 40%. The flow rate of air or O_2 supplied into the bio-scrubber was controlled in between 1 to 10% of the biogas flowrate to ensure that the O_2 level in treated biogas shall be less than 1%.

The biologically-treated biogas was then dried to remove moisture using a chiller dryer. The second stage of H_2S removal used activated carbon (Desorex K43J, Donau Carbon, USA) to further reduce the H_2S content to targeted level of Bio-CNG. The targeted reduction of H_2S after bio-scrubber and activated carbon was less than 900 ppm and 10 ppm, respectively. Ultra-low H_2S biogas was supplied to chiller cooling system before entering the first stage compressor unit. Mechanical reciprocating-type compressor was used to compress the gas from approximately 250 millibar to about 14 bar. The treated and compressed biogas was passed through a two-stage membrane separation system (Air Products, USA) to remove CO_2 from biogas. 2 stages membrane separation was used to increase the CH_4 purity and reduce CH_4 losses in off-gas composition. CH_4-enriched biogas was then compressed to 250 bar for storage using gas cylinder skid or refilling to gas cylinder container trailer for product distribution.

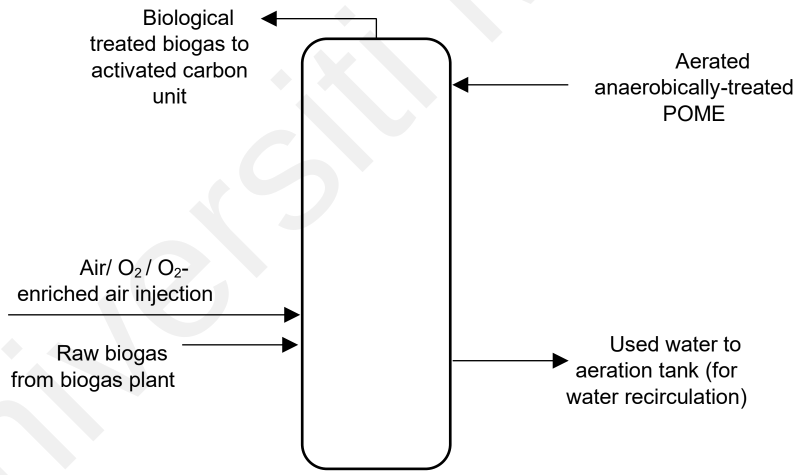

Figure 3.5: Process flow for bioscrubber used for H_2S removal study from raw biogas

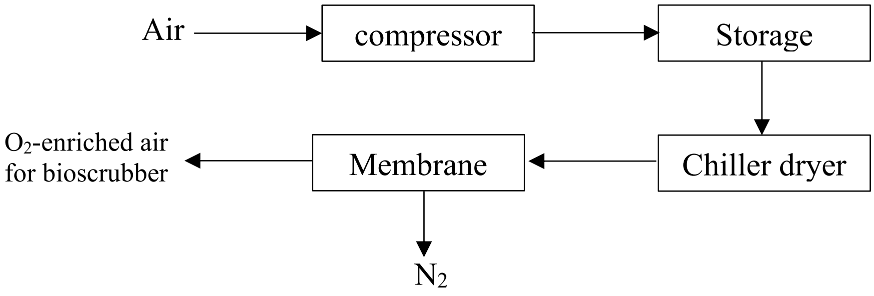

Figure 3.6: Production of O_2-enriched air for H_2S removal using bioscrubber system

Table 3.4: Designed and process parameters of bioscrubber system

Parameter	Value
Diameter, m	2.5
Column height, m	8
Packing material	Structured packing medium
Biogas flowrate, m^3/h	600
Liquid flowrate, m^3/h	50-60
Air flowrate, m^3/h	60

Table 3.5: Major operation units of biogas upgrading system

Equipment	Brand/ supplier	Power capacity, kW
Bioscrubber	Periforce, Malaysia	6.2
Dryer system	-	15
Activated carbon vessel	-	-
1st stage compressor	Safe, Italy	132
Compressor cooling system	-	16
Membrane separator unit	Air Product, USA	-
2nd stage compressor	Safe, Italy	70

3.6.5 Characterisation of Biogas and Bio-CNG from POME

The composition of raw biogas from covered lagoon digester and biologically-treated biogas from bioscrubber were measured using a portable gas analyser (MRU Optima 7 Biogas, Germany). The measurement was conducted on hourly basis. Performance of bioscrubber for H_2S removal using 3 different approaches, namely i) air injection, 2) purified O_2 and 3) O_2-enriched air was studied. The study was conducted at different biogas flowrate varies from 150 to 650 m^3/hr for an hour. The gas composition was measured for a period of an hour at every 10 minutes interval. The average data of H_2S removal was calculated once the H_2S reading was consistent for a minimum period of 30 seconds.

Gas composition after carbon filter unit and final product (Bio-CNG) were measured and recorded using a fixed-automated gas analyser (Awiflex, Germany) installed at the Bio-CNG plant. The gas compositions, namely CH_4, CO_2, O_2 and H_2S were automatically measured and recorded in between 30 minutes to an hour throughout the production process. The N_2 in the biogas was determined by difference of the total recorded gas component. The removal efficiency of H_2S and CO_2, as well as the increased concentration of the CH_4, were determined using Equations 3.14, 3.15 and 3.16 as described by Rattanaya et al. (2021). The raw biogas and final product were also sampled and analysed using gas chromatography (GC) (Agilent 7890, USA) according to ASTM-D1945-03 (Standard test method for analysis of natural gas by GC) and GPA 2286-00 (Method for the extended analysis of natural gas and similar gaseous mixtures by temperature program GC). The analysis was performed by ERALab Sdn. Bhd. The calorific value, specific gravity (relative density) and Wobbe index of the produced Bio-CNG were calculated according to UNE-EN ISO-6976.

$$H_2S_{removal\,\%} = \frac{(H_2S_{\,inlet} - H_2S_{\,outlet})}{H_2S_{inlet}} \times 100\% \tag{3.14}$$

$$CO_{2\,removal\,\%} = \frac{(CO_{2\,inlet} - CO_{2\,outlet})}{CO_{2\,inlet}} \times 100\% \tag{3.15}$$

$$CH_{4\,increment\,\%} = \frac{(CH_{4\,final} - CH_{4outlet})}{CH_{4\,inlet}} \times 100\% \tag{3.16}$$

3.6.6 Economic Analysis of Bio-CNG Production

The economic analysis of the Bio-CNG plant installed in a palm oil mill was carried out for two capital expenditures (CAPEX) scenarios: 1) with Bio-CNG plant only and 2) biogas and Bio-CNG plant. The annual production of Bio-CNG was fixed at 80,000 MMBTu. The CAPEX, maintenance, consumables, operation, utility and personnel costs of the Bio-CNG plant were collected either from the plant operational data and provided by the technology provider. The economic performance was assessed using the discounted cashflow (DCF) method as described by Malek et al. (2017) with a total economic lifespan of 15 years. The DCF determines net present value (NPV), internal rate of return (IRR) and payback period (PBP) of the investment The NPV is defined as a total of cash flow earned throughout the project implementation period, IRR describes project profitability via discount rate at zero NPV and total of years requires to obtain positive cash flow is known as PBP. The following equations were used to determine the NPV, IRR, and PBP (Malek et al., 2017; Yoshizaki et al., 2013):

$$NPV = -S + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_T}{(1+r)^T}$$

$$= -S + \sum_{j=1}^{T} \frac{CF_J}{(1+r)^j} \tag{3.17}$$

$$NPV = -S + \sum_{j=1}^{T} \frac{CF_j}{(1+IRR)^j} = 0 \tag{3.18}$$

$$PBP = \frac{TI}{EAIT} \tag{3.19}$$

where S is intitial investment, RM, CF is cash flow, r is discount rate (10%), T is project term (years), j is jth year, TI is total investment and $EAIT$ earnings after interest and tax.

3.6.7 Environmental Evaluation of Bio-CNG from POME

Environmental performance of Bio-CNG production was evaluated based on total GHG savings or reduction by biogas capture and displaced energy from Bio-CNG using equations presented in section 3.3. COD value of POME and removal efficiencies after the closed anaerobic digester were obtained from the actual values analysed and measured from the study as described in section 3.6.2. Net GHG savings is calculated using the equation 3.20 as follows:

$$GHG_{net\ savings} = GHG_{biogas\ capture} + GHG_{displaced\ energy} - GHG_{electrcity} \tag{3.20}$$

GHG reduction from potential displaced energy from produced Bio-CNG was calculated using CO_2 emission factor of natural gas which is 0.056 kg CO_2/ MJ (Energy Central, 2023) or 53.06 kg CO_2/ MMBTu (EPA, 2023). The GHG emissions generated from the grid electricity used to produce Bio-CNG was determined using 0.585 t CO_2/ MWh.

3.6.8 Life Cycle Assessment (LCA)

The LCA is a systematic approach to assess the potential impacts of the resources used and the production system, including products and services. This assessment is conducted in accordance with ISO 14044:2006 (Subramaniam et al., 2021). The goal and scope of the LCA for this study were to determine the environmental impacts of the developed biogas upgrading system from POME. The LCA was conducted based on the gate-to-gate assessment. The system boundaries include the starting and end points and the functional unit of the study are summarized in Table 3.6 and Figure 3.7.

The direct production process involves biogas plant operation, pretreatment of raw biogas, upgrading process and storage. Besides, indirect process, inputs or output parameters such as water consumption, off and removed gases (H_2S and CO_2), gas recirculation, compressed air and treated-POME recirculation used in bio-scrubber supports the major processes. The direct production data such as POME flowrate, biogas and Bio-CNG production, utility inputs, chemical and lubricant consumption was collected, quantified and verified from the plant for a minimum period of 6 months to establish the life cycle inventory (LCI). The LCI was used to quantify life cycle impact assessment (LCIA) using the Recipe methodology of Simapro 9.2.0.2 software. The GWP for CH_4 was carried out according to Loh et al. (2017).

Table 3.6: Description of the system boundary and functional unit of the life cycle analysis (LCA) of the bio-compressed natural gas (Bio-CNG) production from palm oil mill effluent (POME) in a palm oil mill

Assessment type	Starting point	End point	Functional unit
Gate-to-gate	Receiving point of the Bio-CNG plant where the raw biogas is received.	Dispensing point of Bio-CNG to the trailer	1 MMBTu of Bio-CNG production

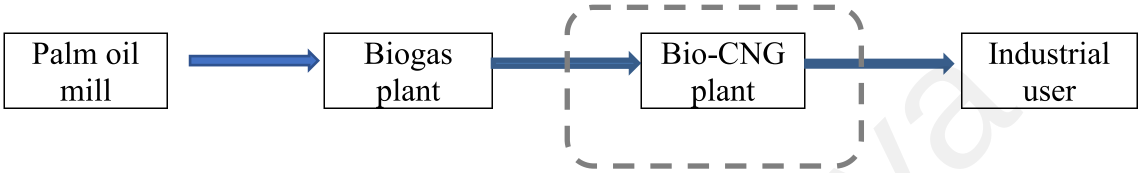

Figure 3.7: System boundary of the life cycle assessment (LCA) study for the production of bio-compresssed natural gas (Bio-CNG) from palm oil mill effluent (POME)

3.7 Safety Precautions

This study involved research activities field works for onsite monitoring, data and samples collection at the project site and laboratory works such as sample preparation and analysis. Therefore, these activities were exposed to onsite safety risks and hazards, and chemical hazards in laboratory. In order to ensure the highest possible level or minimum risks during conducting the research activities, all aspects of safety procedures, precautions, regulations and best practices imposed for the palm oil mill, biogas and Bio-CNG plants and laboratory were adhered throughout the visit to the plant as well as while working in the laboratory. This includes to wear and use an appropriate personal protection equipment (PPE) at the working place and practicing all precaution measures as required. All the material safety data sheet (MSDS) and guidelines and standard operating procedures (SOP) of the equipment provided by the manufacturers were referred and understood. Additionally, waste generated, excess chemicals and unused collected samples were stored in a proper container prior to disposal.

CHAPTER 4: RESULTS & DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained on the RE and GHG savings potential of biogas capture and utilisation from overall scenario (nationwide) and mills having biogas plants in the country. It also presents the status of national biogas development by millers focusing on technology used and utilisation pathway deployed. The potential development of Bio-CNG production from POME in a palm oil mill was evaluated from technical, economic and environmental aspects. The findings of this study are presented and further elaborated accordingly.

4.2 Volume of Wastewater (POME) Generation

As of December 2021, there were 451 palm oil mills in operation nationwide with a total approved annual FFB processing capacity of 112.91 million t. The total FFB processed in 2019 (452 mills), 2020 (457 mills) and 2021 were 98.28, 96.09 and 90.53 million t, respectively and, thus, nationally a depreciation trend observed 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 equipping with biogas plant in 2021 was 40.1 and 29.93 million tonnes, respectively. Figure 4.1 and Table 4.1 show the estimated amount of POME generated from the Malaysian POMs from 2019 to 2021.

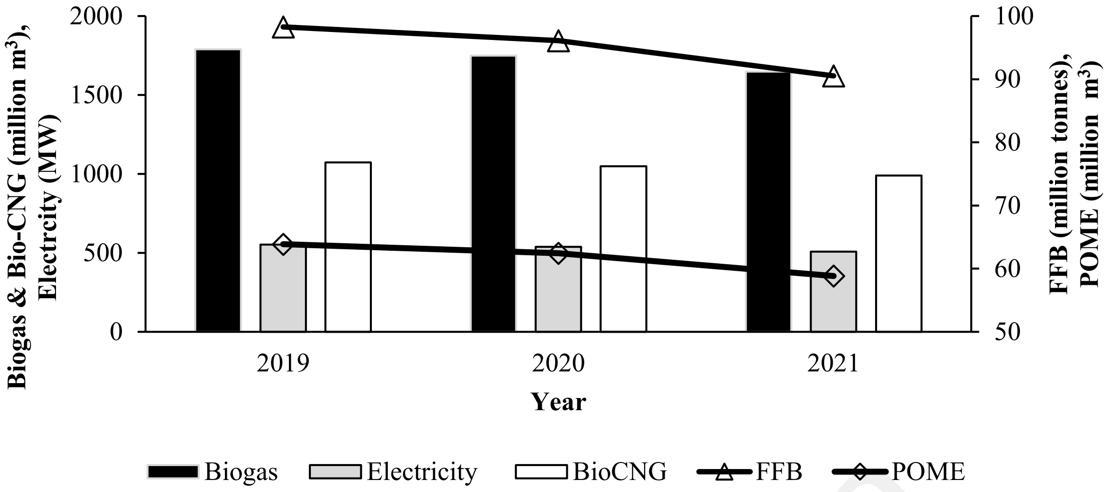

Figure 4.1: Estimated volume of palm oil mill effluent (POME), biogas and bio-compressed natural gas (Bio-CNG), and renewable electricity potential derived from fresh fruit bunches (FFB) processed in the Malaysian palm oil mills (2019 – 2021)

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 large volume is indicative of a huge availability of POME as reported in previous years; 60.88 and 58.5 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 latter 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 t FFB processed

(Kospa et al., 2017), where > 50% of water is discharged as POME (Loh et al., 2013). Besides FFB quantities, the POME generation rate is another major factor in determining POME volume. The average POME rate used for this study was 0.65 m^3 (or t) / t FFB processed. For comparison, the range of POME generation rates from various study is 0.5 – 0.75 t (or m^3) for every t FFB (Tan & Lim, 2019). Thus, based on this range, the minimum and maximum values of POME deviate by 23% and 15%, respectively, from the estimated values calculated using the average POME rate.

The annual trend of FFB processed, either at national or individual mill level, and the POME generation rate are important parameters needed to plan, forecast and design appropriate biogas plant capacity and its potential utilisation options.

Table 4.1: Estimated annual renewable energy potential from fresh fruit bunches (FFB) processed, palm oil mill effluent (POME) and biogas generation

	Year (no. of palm oil mills nationwide)			
	2019 (452)	**2020 (457)**	**2021 (451)**	**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

4.3 Biogas Production from POME

Figure 4.1 and Table 4.1 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 & Biswas, 2019; Muzzammil & Loh, 2020).

The range of biogas yield is 24–32 m^3/m^3 POME using various commercial technologies (Muzzammil & Loh, 2020). Within this range, the minimum and maximum amounts of biogas production are within 14.3% (either lower or upper values) compared to the estimated volume calculated using the mean volume of 28 m^3 biogas/ m^3 POME. 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.

4.4 Renewable Energy Potential of Biogas from POME

Table 4.1 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 & 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 35780 MJ in 2019 to 32960 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 & 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% to the RE share (12916 MW) target by 2025 under the Malaysia Renewable Energy Roadmap (SEDA, 2022). The Roadmap also targets 40% RE share or 17996 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. Based on the CH_4 composition ranges of 55 – 75% in biogas (Shakib & Rashid, 2019; Yusof et al., 2023), the lower and higher values of Bio-CNG potential from POME deviate by 8% and 55%, respectively, from the estimated values calculated using the mean value of 60% CH_4 for this study. 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 4.1 shows the potential energy, electricity and Bio-CNG of 10895 million MJ, 168 MW and 327 million m^3, respectively from 135 mills equipped with biogas facilities, based on 29.93 million t 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.

4.5 Greenhouse gases (GHG) emissions and potential GHG savings

Table 4.2 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 814496, 796346 and 750268 t/yr, respectively. These values are equivalent to 18.76-20.36 million t CO_2eq/yr 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 t CO_2eq/yr calculated based on 896.48 kg CO_2eq/t 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 t CO_2eq) (Ritchie et al., 2020).

The amount of GHG and CH_4 emissions from POME mainly on COD value. The mean COD value of 51000 mg/L used for this study is considered as a lower-end value of typical POME consisted of major sources such as steriliser condensates and clarification wastewater. POME with an additional EFB pressed juice may contain higher COD, approximately in the range of 60000 to 122000 mg/L (Yap et al., 2020; Yusof et al., 2023). Thus, the higher COD contributes to higher CH4 generation leading to higher GHG emissions from open anaerobic digester.

Table 4.2: Total methane and greenhouse gases (GHG) emissions, and potential GHG savings from palm oil mills (POMs) in Malaysia

	Year (no. of POMs nationwide)			135 POMs with biogas plant
Year	**2019 (452)**	**2020 (457)**	**2021 (451)**	**2021**
Methane emissions, t/yr	814 496	796 346	750 268	(247 988)
GHG emissions, million t CO_2eq/yr	20.36	19.91	18.76	(6.20)

Table 4.2: Continued

	Year (no. of POMs nationwide)			135 POMs with biogas plant
Year	**2019 (452)**	**2020 (457)**	**2021 (451)**	**2021**
Potential GHG savings, million t CO_2eq/yr	16.29	15.93	15.00	4.96

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 247988 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). The GHG savings potential from 135 mills with biogas plants were approximately 15.0–16.3 million t CO_2eq annually. These values can be translated into 5.5-6% potential avoided CO_2 emissions from the country's total GHG emissions in 2020 (Ritchie et al., 2020). The calculated actual potential of GHG savings from 135 mills was 4.96 million t CO_2eq/yr, 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 4.3 summarises the potential of GHG savings via displacement of fossil fuel for electricity generation using biogas from POME.

Table 4.3: Potential of greenhouse gases (GHG) savings via biogas capture and electricity generation from palm oil mills (POMs) in 2021

	451 POMs nationwide	**135 POMs with biogas plant**
Potential savings (biogas capture), million t CO_2 eq.	15.0	4.96
Potential savings from electricity generation at 7200 hr/yr, million t CO_2eq/MWhr		
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 t CO_2eq/yr	1.89 (508 MW)	0.66 (168 MW)
Total, million t CO_2eq/yr	16.89	5.62

Note: EF - emission factor.

Table 4.3 shows that an additional 1.89 million t CO_2eq/yr 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 t CO_2eq/yr GHG savings through electricity generation. In total, the country could potentially mitigate 16.89 and 5.62 million t CO_2eq/yr 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.

4.6 Status of 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 (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 technology (Muzzammil & 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 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.

4.7 Status of Biogas Utilisation in Palm Oil Mills

Figure 4.2 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 1 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 4.1). For this purpose, all the plants deployed a typical internal combustion engine, except 1 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 4.3 shows a detailed utilisation breakdown of generated electricity from the POME-based biogas power plant in Malaysia.

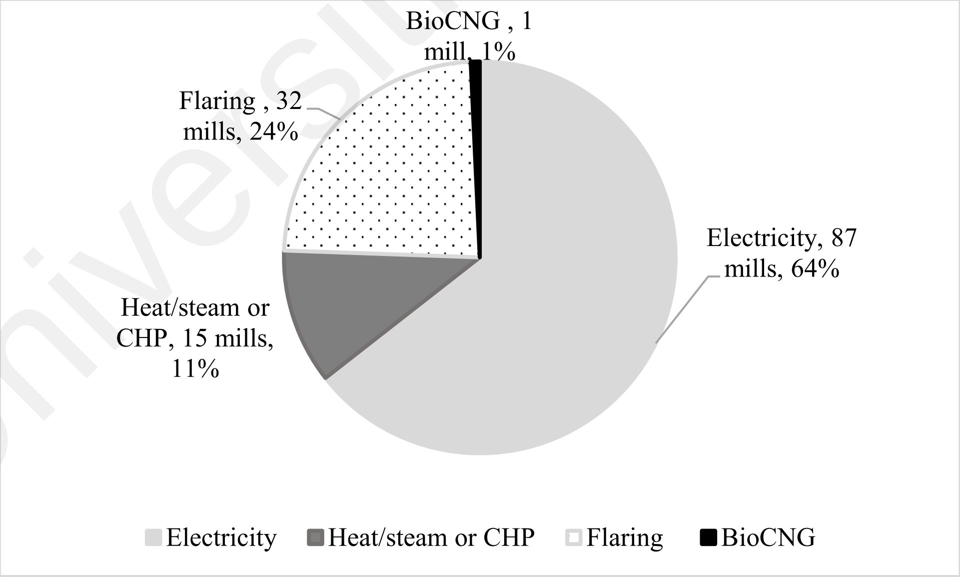

Figure 4.2: Major biogas utilisation in palm oil mills in Malaysia

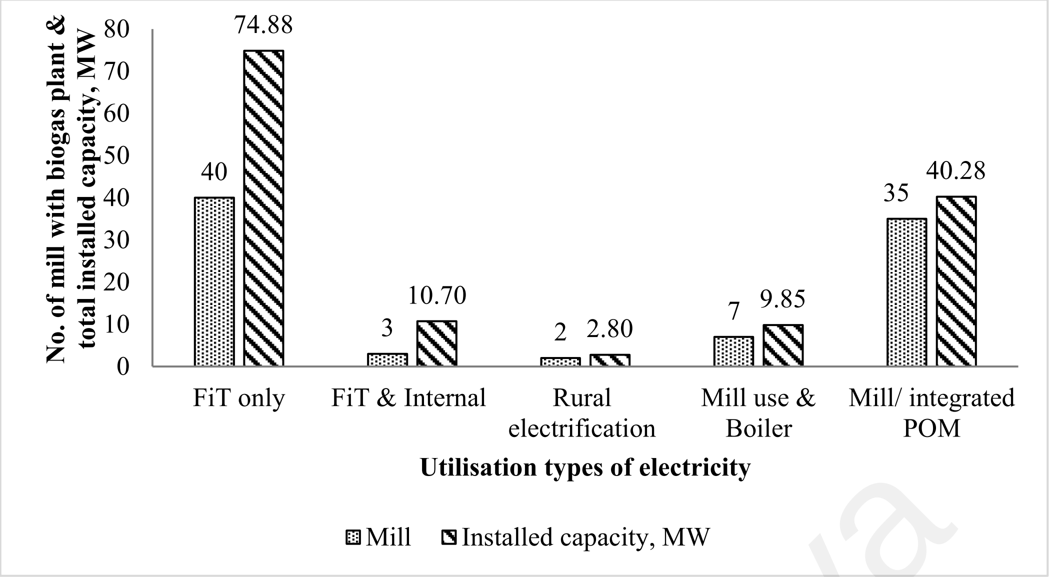

Figure 4.3: Utilisation configuration for electricity generation from biogas in the palm oil mills in Malaysia

Of the 87 mills with biogas plant for electricity generation, 43 plants are grid-connected under the national Feed-in Tariff (FiT) program including 3 plants which also channel part of the electricity generated to the mills for internal use, 2 plants for rural electrification, 35 plants for internal use in the mills or integrated palm oil complexes and another 7 mills for a combined electricity and 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/kWh consisting of RM 0.3184/kWh for basic rate and additional bonuses of RM0.1485/kWh, 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 RM 0.2567-0.2599 kWh^{-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, 7 mills have adopted multiple uses for the captured 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 & 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, 4 plants will commit to FiT, 4 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 & Lim, 2019). To date, 2 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 concentrated compressed CH, 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).

4.8 Development and Evaluation of Bio-CNG Production in a Palm Oil Mill

4.8.1 Biogas and Renewable Energy Potential from POME

The project site is one of the mills operated under FGV located in Kuala Kubu Bahru, Selangor. The selection of the mill for development of Bio-CNG plant was due to several factors; 1) readily available biogas plant which commissioned in 2013, 2) accessibility and strategic location which is closed to Kuala Lumpur (82 km), North-South Expressway Bukit Tagar tol exit (12 km), and 3) Nearby to Rawang, Bukit Beruntung, Serendah and Tanjung Malim industrial areas (< 40 km) for potential product distribution. A 54 t/h installed capacity mill operates with approved processing capacity of 259,000 t/yr. Figure 4.4 and Table 4.4 illustrate monthly and annual FFB processed of the mill from 2019 – 2021.

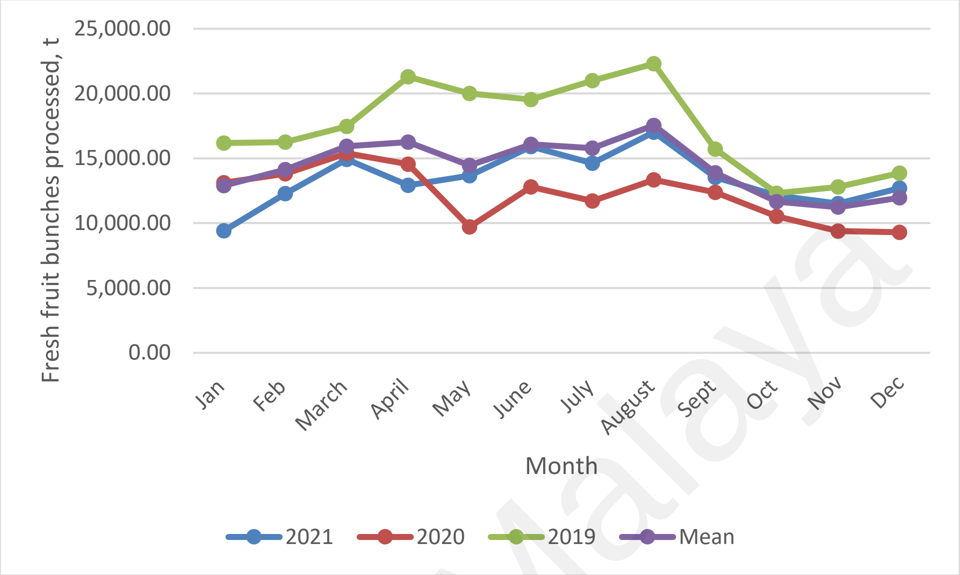

Figure 4.4: Monthly fresh fruit bunches (FFB) processed of the mill in 2019 – 2021

Table 4.4: Estimated annual renewable energy potential from fresh fruit bunches (FFB) processed, palm oil mill effluent (POME) and biogas generation of the palm oil mill

	Approved capacity	**2019**	**2020**	**2021**	**Mean value (2019-2021)**
FFB processed, tonnes	259,000	208,720	146,040	160,610	171,790
POME production, m^3	168,350	135,668	94,926	104,396	111,664
Biogas generation, million m^3	4.71	3.80	2.66	2.92	3.13
Energy potential, million MJ	94.3	75.0	53.2	58.5	62.5
Diesel equivalent, million L	2.68	2.13	1.51	1.66	1.78
Natural gas equivalent, million m^3	2.69	2.14	1.52	1.67	1.79
Electricity (installed capacity), MW	1.45	0.96	0.82	0.9	0.96
Bio-CNG, million m^3	2.83	1.86	1.59	1.75	1.88

The annual total FFB processed of the mill in 2019 -2021 were 208720, 146040 and 160610 t respectively, indicated a tremendous decline in milling capacity utilisation from 80%, 56% and 62% compared to total approved capacity. This depreciation trend was similar to the recent FFB processed nationwide, thus effecting economic performance and waste generation, including POME and biogas production of the mill. The POME generation declined from 135668 m^3 in 2019 to 104396 m^3 in 2021 or mean value of 111,664 m^3 during 2019-2021 periods, as a result of lower FFB processed. As discussed earlier, volume of POME depends on amount of FFB processed. More water is required to process high amount of FFB resulted in high volume of POME generation.

Besides of COVID-19 pandemic, the lower FFB process of the mill was also due to massive replanting programme and stiff competitive for the FFB from surrounding mills. This situation has led to lower POME generation, a feedstock for biogas production. During those periods, a mean value of biogas was estimated about 3.13 million m^3 compared to a potential of 4.71 million m^3 if the mill operated at its full approved capacity (Table 4.4). The current scenario also indicates that the actual RE potential rate from biogas including electricity generation and Bio-CNG production was only at 66.5 % from its approved capacity. At 3181 operation hours annually, biogas flowrate of the mill was estimated at 983 m^3/hr. Based on the approved FFB processing and designed biogas plant capacity, an estimated biogas flowrate of approximately 1000 m^3/hr. Therefore, a 600 m^3/hr is used as the designed capacity of the feedstock for Bio-CNG plant. The remaining will be used as a buffer capacity during the low crop season as witnessed during those periods (2019-2021) or for future expansion of the respective production line.

4.8.2 Characteristics of POME of the Mill

Table 4.5 summarises the characteristics of raw POME and final discharge obtained from the mill, in comparison with the previous study and limits for discharge imposed by the DOE, Malaysia.

Table 4.5: Characteristics of palm oil mill effluent and final discharge of the mill

Parameter, mg/L except for pH,	**Raw POME (This study)**	**Raw POME (previous study)[1]**	**Final discharge (This study)**	**Limit for discharge[1]**
pH	4.6 ± 0.3	4.2	7.8 ± 0.6	5.0 – 9.0
Biological oxygen demand	26772 ± 2929	25000	22 ± 7	100 (50, 20)[2]
Chemical oxygen demand	53833 ± 4429	51000	169 ± 59	-
Total solid	31778 ± 5522	40000	633 ± 408	-
Total suspended solid	16636 ± 1572	18000	22 ± 15	400
Total volatile solid	28001 ± 12063	34000	183 ± 165	-
Oil and grease	9400 ± 300	6000	7 ± 6	50
Ammonical nitrogen	71 ± 11	35 (4-80)	5 ± 3	150
Total nitrogen	556 ± 80	750	15 ± 8	200
Volatile fatty acid	3556 ± 1919	1800 (471-3540)	74 ± 4	-

[1] Bello and Raman (2017)

The characteristic of the raw POME is heavily corresponded to the processing approach adopted by the mill and seasonal trend of FFB. Overall, the raw POME of the mill composed of an average of 26,772 mg/L BOD, 53,8833 mg/L COD, 9400 mg/L O&G and 16,636 mg/L suspended solid. These are comparable to a typical mean value of POME properties for conventional mill as reported in the literature (Bello & Raman, 2017). As samples were collected during low crop season, mainly due to replanting activities and COVID-19 pandemic, where the mill was operating at low capacity or not continuously operated. Therefore, data obtained was much lower compared to reported by Poh et al. (2010) and Yap et al. (2020). Both studies confirmed that higher POME characteristics values during high crop season deviating about 20 to 50% from low crop season, mainly attributed by higher-concentrated organic loading, O&G content and volume of POME.

The BOD and COD concentration of POME during high crop season could be twice and 1.3 times higher, respectively compared to at low crop season (Poh et al., 2010). High organic and inorganic concentration in raw POME contributed to high BOD and COD, approximately > 73,000 and 122,000 mg/L (Yap et al., 2020). POME characteristics is also corresponded to type of wastewater sources generated from the mill. Table 4.6 shows the individual source of POME of the mill which primary-typically from steriliser condensate (sterilisation process) and separator sludge (oil clarification process), and to a limited extent, hydrocyclone waste (kernel recovery process). The characteristics of these two primary sources, were higher from raw POME. This is attributed by high suspended solids and oils, which yet to be removed and recovered in a sand trap and sludge pit, respectively, prior to be discharging to raw POME drainage system.

The characteristics of each wastewater source also depend on the equipment or process used for sterilisation, heavy phase treatment and wet separation of cracked mixture. Compared to other mills, the mill combines all sources of POME including hydrocyclone wastewater as a feedstock for anaerobic digestion. This situation may dilute and contribute to low concentration of raw POME. Other limited source of POME is EFB juice, which is only generated from those mills installed with EFB pretreatment plant. Due to high volume and concentration, additional of this source significantly increases volume and organic content of the raw POME. This contributes to higher concentration level of POME characteristics, particularly COD which is important for higher biogas yield.

Table 4.6: Characteristics of each wastewater sources of the mill

Parameter, mg/L except for pH,	Sterilizer condensate	Separator sludge	Hydrocylone waste
pH	5.3 ± 0.1	4.9 ± 0.2	5.6 ± 0.8
Biological oxygen demand	34906 ± 3744	19908 ± 3416	1960 ± 999
Chemical oxygen demand	61203 ± 18549	48697 ± 15096	5972 ± 2992
Total solid	50667 ± 6848	42383 ± 2932	5042 ± 2675
Total suspended solid	21833 ± 4655	28067 ± 3155	2733 ± 961
Total volatile solid	37967 ± 827	37242 ± 2918	3358 ± 1072
Oil and grease	11400 ± 1000	8183 ± 1134	371 ± 400
Ammonical nitrogen	51 ± 25	49 ± 26	16 ± 14
Total nitrogen	710 ± 84	840 ± 34	34 ± 2
Volatile fatty acid	6593 ± 2614	5485 ± 2751	912 ± 278

The characteristics of raw POME play a crucial factor in the process design and equipment sizing of POME treatment systems, specifically when integrated with a biogas plant. Raw POME with high organic loading, volume and concentration, in specific COD is preferrable for biogas plant operation. The BOD/COD ratio of POME of the mill was more than 0.5 which determines its suitability for biological treatment. Generally, the characteristics of raw POME, such as temperature, pH, O&G and VFA need to be adjusted and controlled to suit to anaerobic conditions. As mesophilic is the most deployed anaerobic conditions in POME treatment, the ideal range or limits of temperature, pH and VFA are 35-40°C, 6.5 – 7.8 and <2000 mg/L (Choong et al., 2018). The temperature and pH of the POME are suitably adjusted via cooling and mixing ponds. To fasten the cooling process of the POME, cooling tower is also installed particularly in mills equipped with biogas plant.

The VFA of raw POME (~3556 mg/L) was higher than the recommended limit of VFA (<2000 mg/L) (Loh et al., 2019a). This will hinder the methanogensis stage of anaerobic digestion, therefore a pretreatment of raw POME is required to improve its condition. The pretreatment system deployed by the mills typically involved O&G removals, followed by mixing and recycling of anaerobically treated POME with raw POME either at mixing ponds or in the closed anaerobic digester. All these approaches which also practised by the mill, is capable to consistently maintain an optimum pH and alkalinity of POME for anaerobic digestion (Yap et al., 2020). Other method is by reducing the organic loading rate to the digester (Poh et al., 2010).

Besides high organic loading, macronutrient content in POME is essential to provide conducive environment and sufficient resources for microorganism growth and anaerobic degradation process (Yap et al., 2020). Table 4.7 shows that POME is rich in various of chemical sources, mainly carbon, oxygen, hydrogen, nitrogen, potassium, phosphorus and magnesium for bacterial growth. The C/N ratio in the raw POME from the mill (< 28) was within the methanogenic bacteria require optimum ratio (< 30), hence provides balanced nutrients and good condition for biogas production (Bukhari et al., 2014). Results obtained from this study indicate that high organic and nutrient contents of the raw POME generated from the mill are sufficient and suitable for biological treatment, specifically via closed anaerobic digester and followed by aerobic system.

Table 4.7: Physico-chemical and elemental analysis of palm oil mill effluent

Parameter	Raw POME (This study)	Raw POME (Loh, 2017)	Raw POME (Ahmad et al., 2011)
Moisture content, wt.%	6.4 ± 0.1	93.0 ± 1.7	-
Volatile matter, wt.%	73.5 ± 1.1	77.1 ± 1.6	-
Ash content, wt.%	14.4 ± 0.2	15.2 ± 2.2	-
Fixed carbon, wt.%	5.7 ± 1.0	-	-
Calorific value, MJ/kg	21.0 ± 0.04	17.0 ± 0.6	
Carbon, wt.%	45.9 ± 0.4	50.0 ± 7.6	
Hydrogen, wt.%	7.7 ± 0.03	15.8 ± 5.5	
Nitrogen, wt.%	1.64 ± 0.04	2.0 ± 0.2	3.9
Sulphur, wt.%	0.4 ± 0.04	ND	4.6
Oxygen, wt.%	44.37	46.9 ± 0.9	
Phosphorus, wt.%	0.83	0.18	1.2
Potassium, wt.%	4.59	1.85	2.0
Magnesium, wt.%	1.61	0.25	0.9
Boron, mg/L	9.66	-	180
Zinc, mg/L	51.2	-	158
Ferum, mg/L	2472	500	1.9

Table 4.7: Continued

Parameter	Raw POME (This study)	Raw POME (Loh, 2017)	Raw POME (Ahmad et al., 2011)
Manganese, mg/L	127	-	550
Calcium, mg/L	1.41	ND	1.6
Copper, mg/L	41.4	-	243
Natrium, mg/L	74.9	ND	1456
Plumbum, mg/L	ND	ND	ND
Nickel, mg/L	7.1	-	4.85

*ND = not detectable

4.8.3 Performance of POME Treatment System and Biogas Plant

The performance of the POME treatment system of the mill is subjected to its ability to comply to discharge limits imposed by the DOE. Meanwhile, the biogas plant performance using covered lagoon digester technology was measured with the organic degradation efficiencies, particularly BOD and COD reduction or removal efficiencies. Table 4.5 shows that all the analysed regulated final discharge parameters of the mill complied to the current legislative requirement imposed by the DOE. The final discharge parameters and its limits applied to the mill are pH (5-9), BOD (<100 mg/L), TSS (<400 mg/L), O&G (50 mg/L), AN (<150 mg/L) and TN (200 mg/L). This is attributed by combined closed anaerobic digester and conventional POME treatment system with sufficient HRT and capacity to efficiently treat POME to acceptable discharge levels.

Overall, the removal rates of BOD, COD, TSS and O&G in final discharge of fully treated POME were more than 99.6%. The AN and TN removal efficiencies of final discharge were 93.0 and 97.3%, compared to raw POME values. Figure 4.5 shows that high BOD and COD removal efficiencies were consistently recorded (higher than 98.0 and 94.4%) from anaerobic treatment of POME via covered lagoon system. The efficiencies obtained were in the range of 98.0 – 98.8% and 94.4 – 96.2% of BOD and COD, respectively in six months duration. The results obtained were comparable to the findings obtained by Yap et al. (2020) at two mills deployed covered lagoon digester. The study also concluded that a typical open ponding was the most ineffective anaerobic treatment for POME, with BOD and COD removal efficiencies were only about 70 and 54%, respectively.

Figure 4.5: Removal efficiencies of biological oxygen demand (BOD) and chemical oxygen demand (COD) using covered lagoon digester

Table 4.8 shows the characteristics of anaerobically treated POME via covered lagoon digester (this study) and the characteristics of the final discharge from previous studies. The anaerobically treated POME of the mill contains on average of 414 mg/L BOD, 2411 mg/L COD, 343 mg/L TSS and 0.12 mg/L O&G. These results shows that the closed anaerobic digester deployed by the mill was very efficient and capable to significantly reduce the organic loading, TSS and O&G to the values that closed or better than the final discharge of previous studies (via conventional system). Thus, improved the final discharge quality and facilitated the mill to comply to the DOE's limits. The lower COD and O&G values after anaerobic treatment which is equivalent to higher removal efficiencies proportionated to a higher biogas production.

Table 4.8: Characteristics of anaerobically treated palm oil mill effluent (POME) of the mill and the final discharge of POME

Parameter, mg/L except for pH and temperature (°C)	This study (ex-anaerobic digester)	Final discharge			
		This study	Yap et al. (2020)	Bello and Raman (2017)	Shahrifun et al. (2015)
Chemical oxygen demand	2411 ± 471	169 ± 59	1767 ± 27	4500	3234 - 3624
Biochemical oxygen demand	414 ± 126	22 ± 7	936 ± 7.12	580	249 - 267
Total suspended solid	343 ± 139	22 ± 15	6667 ± 1018	130	1635-1875
Total nitrogen	297 ± 66	15 ± 8	-	127	-
Oil and grease	1200 ± 1000	7 ± 6	-	-	-
pH	6.7 ± 0.2	7.8 ± 0.6	8.41 ± 0.003	8.4	-

The covered lagoon system using a geo-membrane canvas is a high-rate bioreactor that degrades organic matters to generate and capture biogas in a controlled anaerobic digestion with shorter HRT. The mixing mechanism deployed of the digester is based on hydraulic system via a continuous raw POME feeding (through 18 perforated feeding pipes) and recirculation of anaerobically-treated POME. This is to ensure that the raw POME is constantly mixed with the treated POME uniformly as well as having a maximum contact between them and sludge throughout the digester. The sludge builds up and settling process is prevented and minimised in the covered lagoon. The anaerobically-treated POME is also recirculated and mixed with the raw POME in the mixing tank prior to be feeding to the cover lagoon system. All these approaches provide a conducive condition of the POME for methanogenesis stage and to efficiently degrade the organic matters for post-anaerobic treatment (Yap et al., 2020).

Yap et al. (2020) also mentioned that the covered lagoon system with hydraulic-based mixing system was much efficient than biogas recirculation system. Although efficient, the anaerobically-treated POME from the covered lagoon digester is still required a post treatment.

4.8.4 Characteristics of Raw Biogas

The characteristics of raw biogas generated from POME treated using the covered lagoon anaerobic digester monitored for six months monitoring period is shown in Figure 4.6. Table 4.9 reports the average composition of raw biogas, including a comparison with other studies.

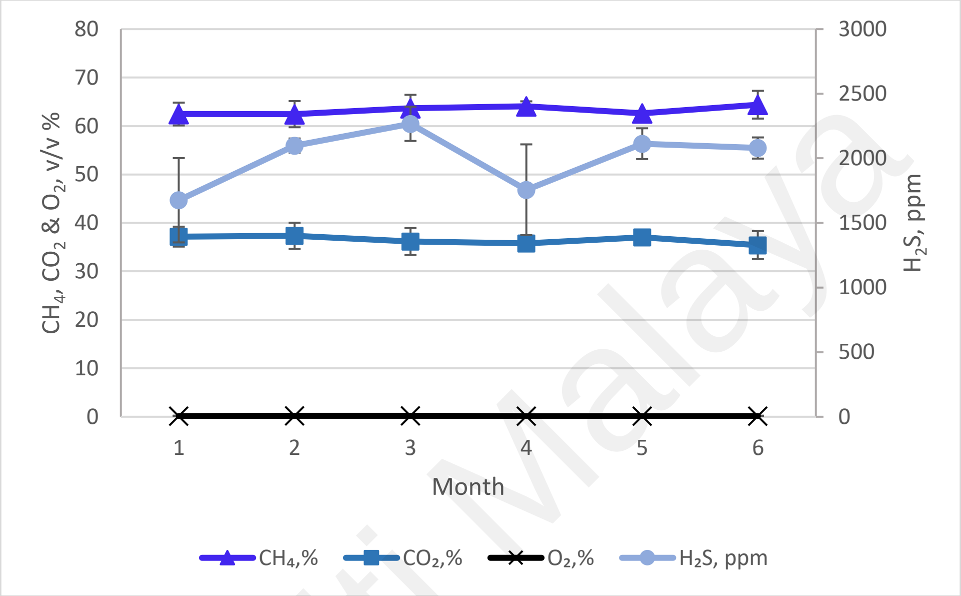

Figure 4.6: Raw biogas compositions throughout the monitoring period

Table 4.9: Summary of raw biogas composition from covered lagoon anaerobic digestion of palm oil mill effluent (POME) and other studies

Component, (v/v)	Mean value (range, if any)		
	This study	Ubaidah et al. (2016)	Mohd Yusof et al. (2023)
CH_4, %	63.20 ± 2.16 (59.4 – 67.4)	63.9 ± 2.8 (58.7 - 68.5)	58.6 – 62.8 (55.74 – 64.02)
CO_2, %	36.54 ± 2.10 (32.38 -39.80)	31.9 ± 2.6 (27.6 – 37.6)	(31.81 – 43.57)
O_2, %	0.17 ± 0.05 (0.10-0.20)	-	(0.01 – 1.04)
H_2S, ppm	2000.76 ± 287.26 (1417-2210)	1453 ± 267 (1002 – 1808)	653.91 - 1291.30 (246 – 1887)

The raw biogas generated from the covered lagoon anaerobic digester contains an average of 63.2 % CH_4, 36.5% CO_2 and traces of O_2 and H_2S with mean concentration of 0.17% and 2000 ppm, respectively. These mean values were within the ranges and comparable to raw biogas composition obtained from the previous studies using commercial digester tank (Ubaidah et al., 2016) and in-ground lagoon (Mohd Yusof et al., 2023). As major components in biogas, CH_4 concentration is inversely proportional to CO_2 content throughout the six-month monitoring period. During that period, the average composition of CH_4 was consistently more than 60% with its minimum and maximum concentration were recorded at 59.4 and 67.4%, respectively. These ranges indicates a healthy anaerobic digestion process in the digestor as reported by Muzzammil and Loh (2020).

The consistent and stable biogas composition, in particular CH_4 and CO_2 was attributed to the consistency of the COD or organic loading rate (OLR) and COD removal rate which was maintained above 50,000 mg/L and 95% efficiencies, respectively. The condition of methanogens during acetogenesis process influences the major biogas component composition. Weak methanogens activity to consume CO_2 resulted in high CO_2 and low CH_4 concentrations in biogas (Mohd Yusof et al., 2023). The presence of H_2S in biogas mainly due to sulphur content in FFB. Processing of FFB for CPO generates effluent containing sulphur in traces. Sulphur is required for microbial growth in AD, however high sulphur may create adverse effect to methanogens. Sulphate-reducing bacteria can utilise and reduce sulphate to H_2S during AD. Although unwanted, H_2S in biogas indicates an adequate amount of sulphur for toxic effect removal of heavy metals.

The O_2 concentration is very limited and comparable to H_2S composition, approximately less than 0.2% or 2000 ppm. Theoretically, O_2 presence in biogas is unlikely under anaerobic condition, but it is relatively normal O_2 can be in digester together with N_2 unintentionally. This is attributed to the plant is operated and integrated with aerobic-based process and open surrounding system such as cooling, feeding and mixing of the raw feedstock (Botheju & Bakke, 2011). O_2 is also detected due to leaking or during gas composition sampling. O_2 is a toxic agent and inhibitor to AD, thus needs strictly avoided in digester.

The chemical energy in biogas is stored in form of methane. the higher methane composition indicates better quality of biogas generation with higher energy content as fuel. The analysis results of raw biogas composition using gas chromatography (mol,%) were found to contain 63.35 % CH_4, 36.21 % CO_2, 0.42 % N_2 and 0.03 % O_2. These results were comparable to the values obtained from the gas analyser. N_2 presence is an indicator of air leakage into the covered lagoon or during sampling. Based on these values, the real gas density, real gas Wobbe Index, gross and nett CV calculated based on ISO 6976-95 were found as 1.1123 kg/m^3, 20.35 MJ/kg, 23.92 and 21.53 MJ/m^3 respectively. As comparison, biogas density is in the ranges of 1.1 -1.2 kg/m^3 and the gross and nett CV of biogas containing 55 – 75% CH_4 is 22 -30 and 19 -26 MJ/m^3. Thus, the analysis results are a pioneering work, particularly in determining raw biogas properties involving CV and density from actual on-site monitoring study of biogas from POME.

4.8.5 Technical Evaluation of Bio-CNG Production from POME

Production of Bio-CNG from POME involves 3 major subsequent processes, namely pretreatment for H_2S removal, biogas upgrading for CO_2 removal and compression process for storage and transportation purpose. The production process was based on the targeted Bio-CNG quality (vol.%) as follows: i) >92% CH_4, ii) <10% CO_2, iii) <1% O_2 and iv) <10ppm H_2S. The first stage of Bio-CNG production is a pretreatment process to remove H_2S from raw biogas. Raw biogas from POME comprises approximately 2000 ppm H_2S was preliminary treated using biological method via biofilter or commercially known as bioscrubber. Through this, the effect of bioscrubber operated with 3 different conditions were studies, namely with i) air injection, ii) purified O_2 injection and iii) O_2-enriched injection. Figure 4.7 to 4.9 illustrate the reduction profile or trend of H_2S in raw biogas using these 3 conditions at different biogas flowrate for 1-hour monitoring. Figure 4.10 summarises the removal efficiencies obtained from these 3 methods at different biogas flowrate.

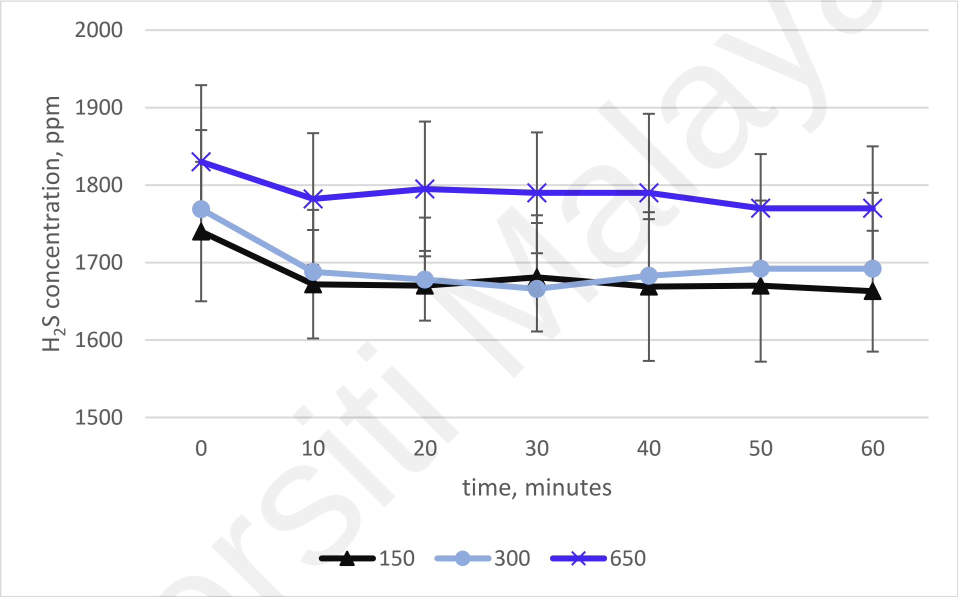

Figure 4.7: Removal of hydrogen sulphide using bioscrubber with air injection at different biogas flowrate

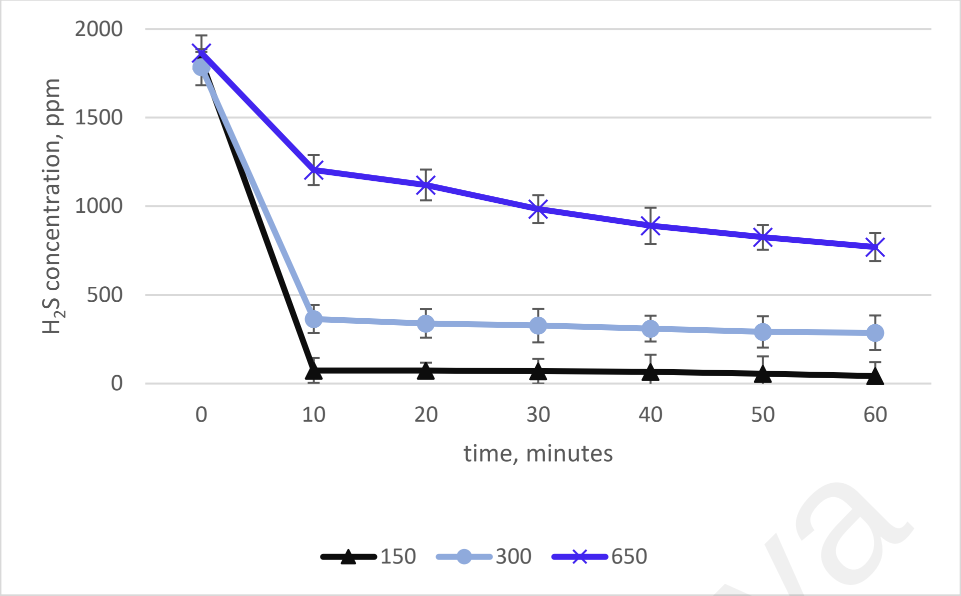

Figure 4.8: Removal of hydrogen sulphide using bioscrubber with compressed oxygen injection at different biogas flowrate

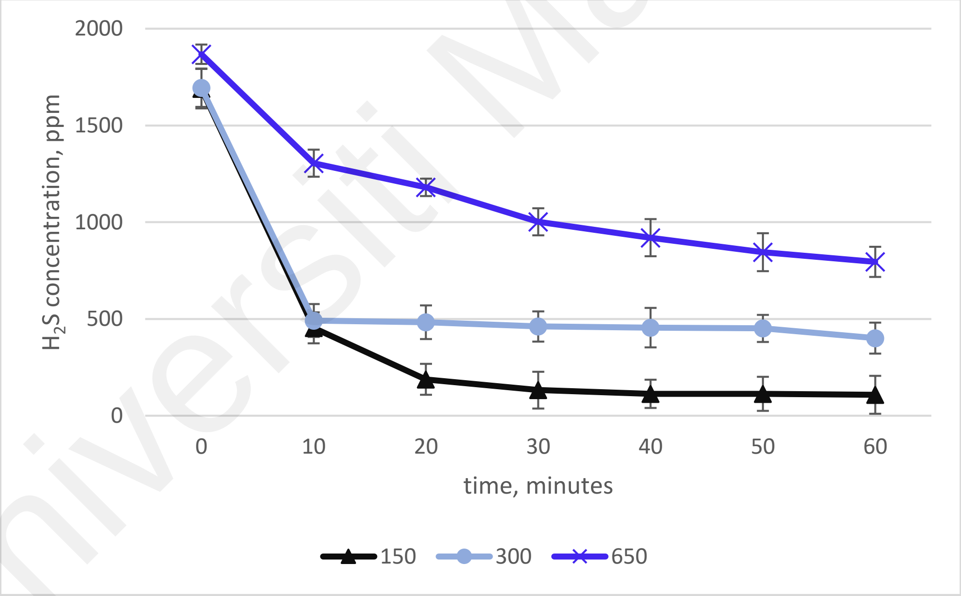

Figure 4.9: Removal of hydrogen sulphide using bioscrubber with oxygen-enriched air injection at different biogas flowrate

Removal efficiencies of H_2S with bioscrubber injected with air at 150, 300 and 650 m^3/hr biogas flowrate were 4.43%, 4.35% and 3.29%, respectively. These results were comparable to findings conducted using a bioscrubber only, indicated that air added into the bioscrubber was insignificant in reducing H_2S. The study also shows that the higher biogas flowrate, the much lower removal rate of H_2S was achieved. Monitoring of H_2S removal with purified O_2 and O_2-enriched air were injected or added to the bioscrubber shows comparable positive results. At the maximum biogas flowrate of 650 m^3/h, the highest H_2S reduction efficiency was achieved with O_2 injection (58.3%) and followed by O_2-enriched air injection (57.4%). As comparison, a typical biofilter used in palm oil mills to remove H_2S in biogas resulted in >80% removal efficiencies (Promnuan & Sompong, 2017). The difference may due to high biogas rate and suitable conditions for the growth of sulphur oxidizing bacteria (SOB).

The findings also show that both methods could reduce H_2S less than 800 ppm within 1-hour monitoring period, with the potential of further H_2S reduction is possible. Thus, continuous and longer period of bioscrubber operation with these methods is recommended in order to achieve much lower H_2S after bioscrubber treatment. The removal efficiencies of H_2S are inversely proportional to biogas flowrate and H_2S concentration. This means that increasing H_2S concentration and biogas flowrate reduces the H_2S removal rate (Zulkefli et al., 2016). These findings clearly indicated the concentration of O_2 either in purified or O_2-enriched air facilitates to higher H_2S removal.

Bioscrubber operation is based on oxygen presence either in air or purified O_2 that added to bioscrubber. Air or O_2 addition facilitates the growth of aerobic SOB on the filter bed which degrades and oxidises H_2S into elemental sulphur (Ryckebosch et al., 2011). There are several drawbacks of using this method, in particular safety issue related to explosive potential of O_2 content in methane mixture and dilution of methane/ biogas concentration due to N_2 presence in air that affected CH_4 content in final product. N_2 is inert and most of upgrading biogas technology are unable to separate N_2. Thus, a direct use of air or O_2 supply requires close monitoring and control to ensure high H_2S removal efficiency is achieved without jeopardising biogas quality for subsequent processes of

Bio-CNG production. For this purpose, O_2 in biologically-treated biogas was controlled to be less than 1%. This target was achievable by controlling the O_2 or O_2-enriched air throughout the production process. Nevertheless, O_2 after biological desulphurisation is added advantage for the subsequent-further desulphurisation using activated carbon as applied in this study.

Although purified O_2 offered better removal efficiency without diluting effect, however the process contributes additional cost to Bio-CNG production. It was estimated that dosing of pure O_2 into bioscrubber contributed about RM 0.50/ MMBtu. Due to economic advantage, bioscrubber with O_2-enriched air injection was selected as a first and primary desulphurisation step for commercial exploitation, prior to further removal of H_2S to less than 10 ppm by adsorption process using activated carbon. The concentration of H_2S after activated carbon filter was less than 5 ppm, regardless of the H_2S level fed into the activated carbon system. This is attributed by versatile properties of activated carbon such as high in surface area, porosity and surface chemistry that resulted in high adsorption capacity and fast reaction kinetic (Zulkefli et al., 2016). Higher loading of H_2S to activated carbon filter will reduce the removal efficiency and lifespan of activated carbon, require more cost and time for replacement of activated carbon.

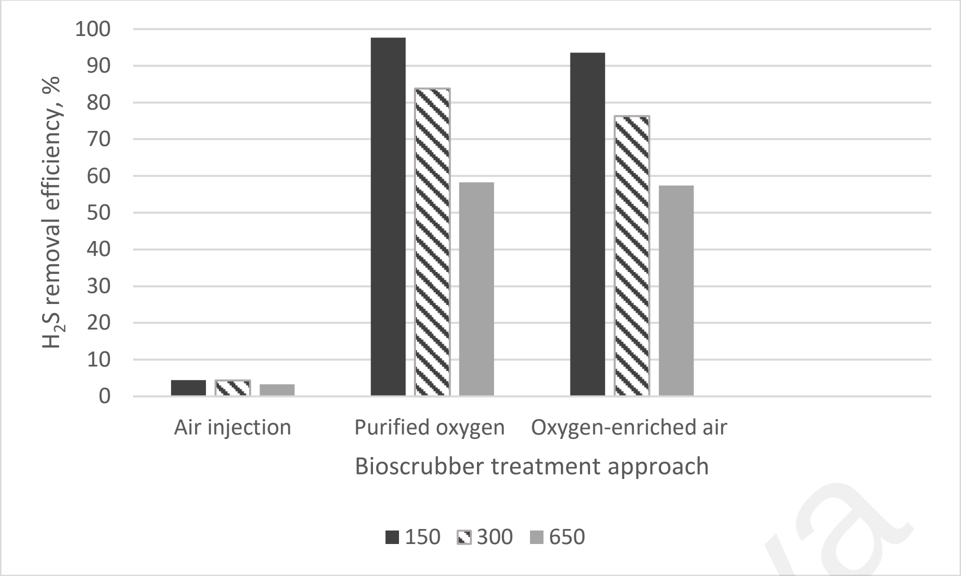

Figure 4.10: Removal efficiencies of hydrogen sulphide using bioscrubber with air, purified and oxygen-enriched air injection

The reduction efficiency of H_2S from biologically treated biogas (H_2S content < 800ppm) using activated carbon was > 99.3%. The overall H_2S reduction efficiency from raw biogas using a combined biological and adsorption process was found to achieve > 99.7%. Nevertheless, the efficiencies might be slight varies depending much on the fluctuating of raw biogas compositions which were not taken at the same time as biologically treated biogas. These findings show that the combined method is cost-effective desulphurisation process that suitable for Bio-CNG production. Through this, 2 major steps are involved, namely primary stage to reduce the raw H_2S level to certain level using inexpensive biological method. The 2nd stage involves a fine-tuning process in which to further reduce the biologically treated H_2S to ultra-low level according to end-user requirements via high-end technologies such as activated carbon.

The ultra-low H_2S raw biogas was then upgraded to high methane by removing CO_2 using membrane separation. Figure 4.11 and Table 4.10 show mean value of Bio-CNG produced from POME. The Bio-CNG produced from biologically treated H_2S using O_2-enriched air comprised an average 93.96% CH_4, 2.82% CO_2, 0.46% O2, 2.76 ppm H_2S

and remaining 2.76% of N_2 calculated by difference. By taking the mean values of biogas compositions obtained from this study, the upgrading process had achieved a 92.2% removal efficiency for CO_2 thus increasing methane content to 93.96% (increment efficiency up to 48.8%). This CO_2 removal efficiency was comparable to study conducted by Park (2021) who had obtained 94% removal efficiency using membrane technology. Methane content of 94% was slightly lower compared to 98% methane as reported by Park (2021). However, it was higher than findings reported by Starr et al. (2014) and Dussadee et al. (2014) using membrane with < 90% CH_4.

Membrane technology is known for its moderate purity %, compared to other technologies, mainly due to system design limitations and higher methane loss. The methane purity can be increased by increasing the membrane unit or using multiple separation stage. Besides a lower CO_2 removal efficiency, the lower CH_4 obtained was due to N_2 presence in biogas from the H_2S pretreatment using O_2-enriched air. Nevertheless, the CH_4 content and other component in Bio-CNG were comparable and in the acceptable ranges either local natural gas quality or buyer requirement.

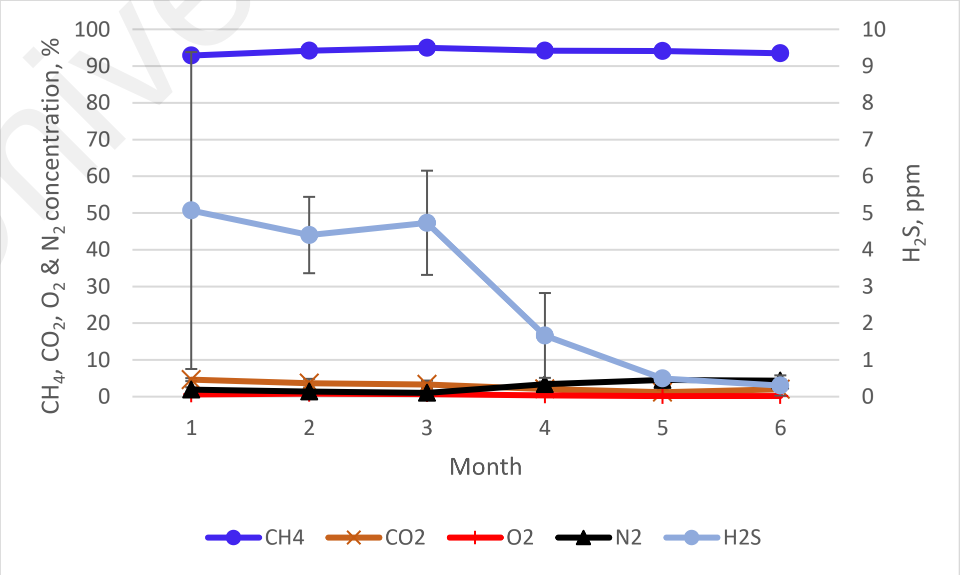

Figure 4.11: Mean value of bio-compressed natural gas composition

Table 4.10: Summary of bio-compressed natural gas composition from palm oil mill effluent and comparison to other studies

Component	Raw biogas (this study)	Bio-CNG (this study)	Dussadee et al. (2014)	Park (2021)	Natural gas quality*
CH_4, %	63.20 ± 2.16	93.96 ± 0.72	89.35	98.0	>92
CO_2, %	36.54 ± 2.10	2.82 ± 1.27	10.05	2	<2.0
O_2, %	0.17 ± 0.05	0.46 ± 0.27	0.02	-	<0.2
H_2S, ppm	2000.76 ± 287.26	2.78 ± 2.2	<0.01	1	< 5
N_2, %	-	2.76 ± 1.53	-	-	-
Other hydrocarbon, %	-	-	-	-	6

*Nasrin et al. (2020)

The analysis results of Bio-CNG composition using gas chromatography (mol,%) show that Bio-CNG contains 93.79 % CH_4, 3.9 % CO_2, 2.04 % N_2 and 0.03 % O_2. These results were comparable to the values obtained from the fixed gas analyser, except for N_2 which was calculated by difference. The analysis results using GC confirmed the presence of N_2 in Bio-CNG, due to deployment of O_2-enriched air in bioscrubber. Based on these values, the real gas density, real gas Wobbe Index and gross CV of Bio-CNG calculated based on ISO 6976-95 were found as 0.7327 kg/m^3, 55.65 MJ/kg and 35.78 MJ/m^3 respectively. These gas properties comparable and within the specifications of the commercial natural gas available in Malaysia. The findings obtained from this study show that a combined biological and adsorption method for H_2S removal and followed by membrane separation is technical feasible technology to produce Bio-CNG from POME where the product quality is significantly improved for efficient and wider biogas applications.

4.9 Economic Analysis of Bio-CNG Production

The economic analysis was conducted based on two different CAPEX scenario, i) with Bio-CNG plant only and ii) biogas capture facility and Bio-CNG plant. Based on this study, CAPEX for Bio-CNG plant only was RM 7.0 million and a minimum additional RM 5 million is required for the project development with a biogas plant, making the total investment of RM12.0 for complete biogas upgrading plant. Operational expenditure (OPEX) mainly involves electricity, consumable (activated carbon and lubricant) and maintenance cost contributes about RM 25.50/ MMBTU Bio-CNG. The average natural gas selling of RM 36.42/ MMBTu by Gas Malaysia Berhad was used as a baseline to determine a minimum selling price of Bio-CNG from POME. Table 4.11 summarises the economic analysis conducted for two project scenarios of Bio-CNG plant in a palm oil mill.

Table 4.11: Economic analysis of the 400 m^3/hr of bio-compressed natural gas (Bio-CNG) production plant from palm oil mill effluent (POME)

Description	**Value**	
	Bio-CNG plant only	**With biogas and Bio-CNG plant**
Capital expenditure (CAPEX), RM (million)	7.0	12.0
Annual production, million m^3 @ 7200 hr/ yr	2.46 (~80,000 MMBTu)	
Assumption : • Bio-CNG selling price @ RM 40.00 – 46.00/ MMBTu • Operational expenses (OPEX) @ RM 25.50/ MMBTu		
Net present value (NPV) @10%, RM (million)	1.82	0.17
Internal rate of return (IRR), %	14.36	10.25
Payback period, year	6.03	7.50

Investment of Bio-CNG plant to the existing biogas plant offers an attractive internal rate of return (IRR), 14% with a payback period within six years. However, the complete investment of biogas and Bio-CNG plant provided less IRR (10.25%) and longer payback period with the minimum selling price of Bio-CNG is RM 46.00/ MMBTu. Nevertheless, both scenarios provide a feasible option of biogas utilisation compared to other typical uses of biogas. These analysis results also indicate that Bio-CNG is not feasible option for a direct replacement of the subsidised natural gas in the country, based on the current selling price of natural distributed via pipelines. Therefore, the produced Bio-CNG is an alternative to those end users that currently using other than subsidised natural gas such as diesel or medium fuel oil. Thus, selling it at the higher price is possible compared to natural gas.

As a comparison, 1.9 MW grid-connected biogas plant developed in a 60 t/h mill has more attractive IRR and shorter PBP of 29.7% and 3.7 years only compared to Bio-CNG production (Foong et al., 2020). Nevertheless, the Bio-CNG plant is alternative for those mills which are not feasible for grid-connected biogas plant and located nearby to industrial areas or natural gas pipelines. The economic analysis of Bio-CNG plant can be improved by reduction CAPEX and to factor in environmental benefits cost such as CER and incentives either from the Government or private utility companies. The attractive Bio-CNG investment also depends on the technology used and business approaches including product distribution. For instance, membrane technology has the shortest PBP and most economical option compared to other upgrading technologies for pipeline quality of Bio-CNG (Mohtar et al., 2018). Water scrubber technology provides the highest economic performance for Bio-CNG distribution using trucks (Hong et al., 2021).

By introducing carbon trading price of RM 80/t CO_2, 227 biogas upgrading plants can be constructed in Peninsular Malaysia with a total bio-CH_4 production of 56 million m^3/year (Hoo et al., 2017). Supply of biogas via virtual pipelines is more feasible option compared to upgraded biogas, mainly due to higher logistic, compression and upgrading cost of upgraded biogas (Lee et al., 2019). A comparative study of integrated biogas upgrading plant with CO_2 utilisation for microalgae using various upgrading technologies resulted in insignificant profit reduction (Lee et al., 2017). Khan et al. (2017) reported that water scrubbing technology has the lowest maintenance cost, followed by membrane separation, PSA and cryogenic. Thus, the Bio-CNG developers need to investigate all the business options and factors clearly for better return of the investment.

4.9.1 Sensitivity Analysis

A sensitivity analysis was conducted in the economic assessment of Bio-CNG production from POME to evaluate the impact of changes in key variables or assumptions on economic outcomes. The analysis involved varying the Bio-CNG unit price (RM/MMBTu) for both investment scenarios, with RM 36.42/MMBTu, the average natural gas selling price by Gas Malaysia Berhad, serving as the baseline. In the first scenario, involving investment solely in the Bio-CNG plant, a positive NPV with an IRR greater than 10% was achieved when the selling price exceeded RM37/MMBTu. For every RM 1/MMBTu increment of selling price, there will be an approximately 100% increase in NPV, a 12% increase in IRR, and a reduction of half a year in the payback period (PBP). A unit price of RM 40.00/ MMBTu was chosen as minimum selling price due to attractive return and PBP about 6 years only.

For the full investment involving Bio-CNG plant and biogas plant, a positive NPV with an IRR greater than 10% was achieved when the selling price exceeded RM45.20/MMBTu. Hence, a selling price of RM 46.00/MMBTu was selected as the minimum for this economic analysis of full plant. In order to achieve comparable NPV, IRR and PBP to the Bio-CNG plant investment scenario selling at RM 40.00/MMBTu, the Bio-CNG produced from the second scenario investment needs to be sold at RM50.00/ MMBTu. The suitability of investment metrics such as IRR, payback period, and NPV depends on various factors, including selling price. This analysis signifies that variation of selling price is a major contributor to the overall investment return. A positive NPV indicates that the investment is expected to generate value and is typically considered a key indicator of investment viability.

4.10 Environmental Evaluation of Bio-CNG Production

4.10.1 Greenhouse Gases Emissions and Savings

Table 4.12 summarises the estimated methane and GHG emissions to atmosphere, if POME was conventionally treated in the mill from 2019 to 2021. These values were calculated based on mean value obtained from this study. During these periods, the generated amount of CH_4 was in the range of 1277 – 1825 t/yr which is equivalent to 31938 – 45646 tCO_2eq/yr. Based on actual COD removal efficiency of 95.53%, the potential GHG savings of the mill from biogas capture alone were 30510 – 43605 tCO_2eq/yr.

Table 4.12: Total methane and greenhouse gases (GHG) emissions, and potential GHG savings from the palm oil mill

	Approved capacity	2019	2020	2021	Average
FFB processed, t	259,000	208,720	146,040	160,610	171,790
POME, m^3	168,350	135,668	94,926	104,396	111,664
Methane emissions, t/yr	2265	1825	1277	1404	1502
GHG emissions, t CO_2eq/yr	56642	45646	31938	35124	37570
Potential GHG savings, t CO_2eq/yr	54110	43605	30510	33554	35890

The captured biogas which is used for Bio-CNG production with 80,000 MMBTu annually provides an additional GHG savings via displacement of fossil fuel such as natural gas. Based on 53.06 kg CO_2eq/ MMBTU (EPA, 2023), the potential of GHG savings from displacement of natural gas by Bio-CNG is 4431 t CO_2eq/yr. The Bio-CNG plant requires about 1728 MWh annually from grid in which contributes 1011 t CO_2eq/yr of GHG from electricity alone for Bio-CNG production. Thus, the nett GHG savings of 3419 t CO_2eq/yr could be obtained annually if all produced Bio-CNG of the mill used to substitute natural gas. In total, the mill could potentially mitigate 33929 – 47024 t CO_2eq/yr from biogas capture and utilisation for Bio-CNG production. The findings indicate that provides a huge GHG savings for palm oil mill, mainly from biogas capture activity, thus reduce carbon footprint of CPO and significantly improves sustainable image of the palm oil industry.

4.10.2 Life Cycle Assessment (LCA) of Bio-CNG Production

The LCA of Bio-CNG production comprises 2 main studies, namely establishment of life cycle inventory (LCI) and life cycle impact assessment (LCIA). Table 4.13 summarises the LCI which consists of major input parameters and consumables for production of 1 MMBTu Bio-CNG from POME. Major resource and input are raw biogas and electricity for production process, followed by activated carbon that used to remove H_2S in raw biogas to ultra-low level. Captured biogas from the covered lagoon digester is a renewable source and electricity used was solely sourced from the grid. The analysis results show that approximately 17 kWh is required to produce 1 MMBtu, which is equivalent to 0.6 kWh/m^3 or 0.017 kWh/MJ of Bio-CNG produced. Therefore, production of 1 kWh Bio-CNG from POME using membrane technology required approximately 0.06 kWh electricity.

A study reported 0.068 kWh was required to produce 1 kWh biomethane from municipal waste biogas using membrane technology (Starr et al., 2014). The study also reported that electricity consumption to produce 1 kWh biomethane from commercial technologies such as high-pressure water scrubbing, pressure swing adsorption, organic physical scrubbing, chemical scrubbing and cryogenic separation were 0.04, 0.05, 0.06, 0.02 and 0.7 kWh, respectively. High electricity required is mainly attributed to the compression unit, particularly 1st stage compressor. 1st compressor unit is used to increase the biogas pressure from 250 millibar to 14 bar for membrane separation. production of 1 MJ biogas required 2.5 MJ energy input, compared to natural gas which is just slightly higher than 1 MJ.

Data obtained from this study was used to conduct a gate-to-gate life cycle impact assessment (LCIA) using Recipe 2016 method of SimaPro 9.2.0.2. Figure 4.12 illustrates various impact categories of Bio-CNG production from POME.

Table 4.13: Life cycle inventory for production of 1 MMBTu bio-compressed natural gas (Bio-CNG) from palm oil mill effluent (POME)

Input parameter, unit	Value
Activated carbon, kg	0.1
Lubricant oil, l	0.014
Odorant, l	0.001
Electricity, kW	17.0
Raw biogas, m^3	42.34

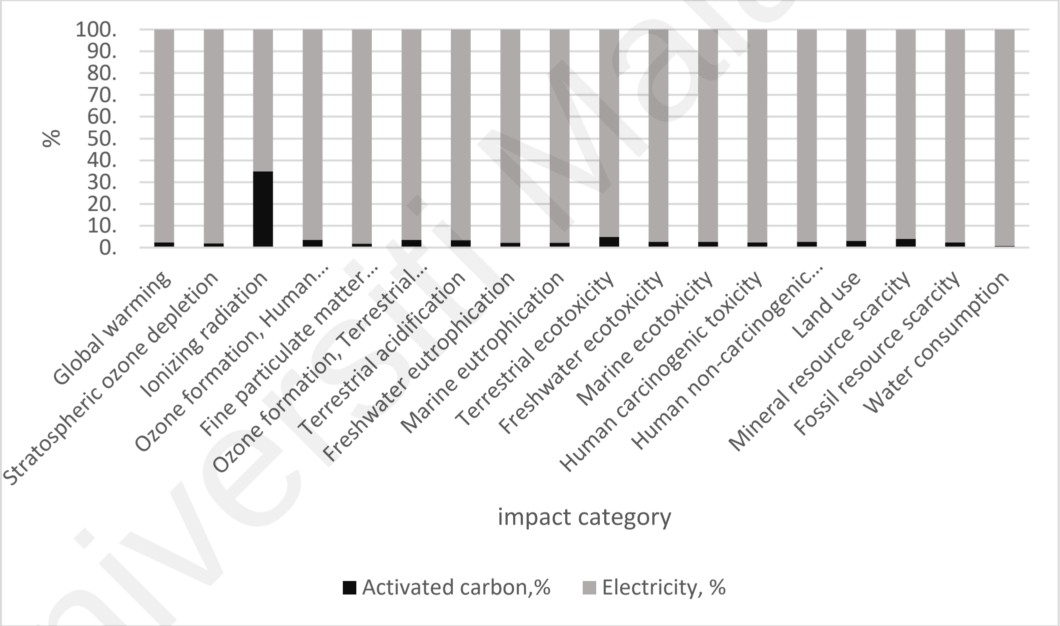

Figure 4.12: Life cycle impact assessment category of bio-compressed natural gas production from palm oil mill effluent

The analysis of LCIA indicates that electricity and activated carbon used were the major impact contributors of the Bio-CNG from POME. Based on Figure 4.12, electricity used was a dominant contributor of each impact categories compared to use of activated carbon with the percentage contribution of each category is more than 95%. The usage of electricity from the grid and activated carbon made from coal contribute mainly to various impact categories. Top five impact categories based on total unit per impact category >

0.5 were global warming, human non-carcinogenic toxicity, terrestrial ecotoxicity, fossil resource scarcity and human carcinogenic toxicity. The production of Bio-CNG contributes in total 14.1 kg CO_2eq for every 1 MMBTU Bio-CNG produced, where 97.6% were from grid electricity. The grid electricity in Malaysia is mainly generated from fossil fuels such as coal, natural gas and diesel, thus directly contributes to other associated impacts of power plant operation such fine particulate emissions and reduction of fossil resources. Repele et al. (2014) reported that the largest environmental impact was contributed by fossil fuel used in the production of Bio-CNG from co-digestion feedstock e.g., manure, silage, whey, corn and grain by-products.

Similarly, activated carbon which was produced from coal will contribute to the similar impact categories. To address these impacts, the use of electricity and activated can be replaced from renewable resources. The Bio-CNG plant can use renewable electricity generated either from oil palm- based biogas or biomass power plant available from the mill, provided sufficient and consistent supply is available. Electricity generation from these resources are established and proven alternative to further support the production of Bio-CNG in a palm oil mill. Palm-based activated carbon, mainly used from palm kernel shell can be an alternative resource to reduce the impact of coal-based activated carbon in Bio-CNG plant. However, further study is required to ensure that the palm based activated carbon is cost-effective consumable in Bio-CNG production.

Although there were many LCA studies conducted on biogas from POME for electricity generation as reported by Raman et al. (2019) and Sharvini et al. (2020), but none of it had assessed or reported LCA study for Bio-CNG production from POME. Electricity generation from POME-based biogas shows a net environmental benefit on global warming and acidification potentials except a negative impact in terms of eutrophication potential. Bio-CNG production contributes slight to global warming compared to positive impact of electricity on this category from biogas. As comparison of Bio-CNG production made from non-POME feedstock, level of GHG of Bio-CNG varies from -36 to 10 g CO_2eq./ MJ compared to 72 g CO_2eq/ MJ of natural gas (Valli et al., 2017). Therefore, Bio-CNG or biomethane provides a carbon-negative substitute for fossil fuels, which its GHG reduction amounting to 200g CO_2 eq/kWh (Adelt et al., 2011). The result obtained from this study was 14.1 kg CO_2eq/ MMBTu is equivalent to 0.014 kg CO_2eq/MJ (14 g CO_2eq/MJ), which is slightly higher than reported values above. However, it is still much lower than GHG emissions reported for natural gas. Therefore, the findings obtained from this study can be used as a benchmark for detailed LCA study of Bio-CNG from POME, in particular for cradle to grave LCA study in the future.

4.10.3 Sensitivity Analysis

A sensitivity analysis was conducted to assess the impact of individual input parameters, particularly from the Life Cycle Inventory (LCI), on the environmental analysis and Life Cycle Assessment (LCA) results by varying the sources of parameters used in the analysis. The LCA revealed that the impact categories were primarily contributed by using on-grid electricity and coal-based activated carbon as consumables. Given that electricity accounted for more than 95% of each impact category, the analysis focused on exploring alternative sources of electricity. Therefore, electricity generated from diesel and renewable energy (RE) resources, such as biogas, was considered.

It is estimated that an average of 0.34 L of diesel is required for every kWhr which emits approximately 0.47 kg CO_2eq/kWh (Ngan, 2002). 1 MMBTu of Bio-CNG requires about 17 kWh of electricity, thus 5.78 L of diesel is consumed with 8 kg CO_2eq of GHG emissions. Though the direct emission factor of diesel is slightly lower than the grid electricity baseline for Peninsular Malaysia (0.585 kg CO2eq/kWh), however the potential emissions from the transportation of diesel, and the higher cost of diesel, including transportation cost may affect overall environmental performance and LCA results, including viability of the project. The use of renewable electricity, particularly from biogas, will significantly reduce the negative impact associated with producing Bio-CNG from POME and directly affect the overall impact categories of LCA. This also facilitates cost-saving measures of Bio-CNG production. Therefore, it is recommended to include this aspect in the future studies of Bio-CNG production from POME.

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATION

5.1 Conclusion

Capturing biogas from POME for RE utilisation is a practical solution to significantly improve sustainable and economic performance of the palm oil mills. This also facilitates in addressing the global issues on energy crisis and global warming. In the first objective, the present work identifies and determines the potential and current status of RE and GHG savings of biogas from POME in Malaysia. The Malaysian palm oil mills could contribute approximately 1.5% and 4% to the national installed capacity and the RE share target in Malaysia by the year 2025, respectively with substantial GHG savings of 15 million t CO_2eq/year if all palm oil mills capture and utilise the biogas. The current scenario indicates that only 30% of palm oil mills installed the biogas plant with energy recovery of 33% from the overall estimated potential. There are still huge untapped potentials of RE from biogas which require proactive and synergised efforts from the industry players in enhancing sustainable image of the industry.

Electricity generation, in particular for FiT is the most deployed utilisation configuration by the millers. In order to intensify, diversify and optimise the biogas, new uses of biogas need to be identified. Bio-CNG has emerged as promising alternative to the typical-conventional biogas utilisation in the country. In the second objective, this study proved that a combination of biological and physical method, followed by membrane separation is a promising and feasible approach to upgrade biogas from POME to Bio-CNG. The upgraded gas comprises an average of CH_4 (~94%), CO_2 (3%), N_2 (<3%) O_2 (<0.5%) and H_2S (<3 ppm), which is comparable to natural gas quality, thus can be commercially used as an alternative to fossil fuel. The results obtained also demonstrate that the integrating biogas and Bio-CNG plant in palm oil mill is a viable business model, technically and economically, in providing commercial and environmental benefits to palm oil industry and industrial users.

5.2 Recommended Future Works

There are a few future works and research that can be applied in order to further explore the potential of biogas and Bio-CNG from POME as follows:

1) Future research should emphasis on new and emerging end-uses either for biogas or Bio-CNG, in particular for off-site applications. Besides Bio-CNG, biogas can be upgraded to other forms of biofuels such as bio-liquified natural gas (Bio-LNG) and biohydrogen production. The potential uses of Bio-CNG as a substitution to fossil fuel either for industrial uses or transportation sector (vehicle fuel) also needs to be further investigated. Upgraded biogas in the biomethane concentration can be further used as feedstock for liquid biofuel production such as kerosene and diesel via reforming and Fishcher-Tropsch synthesis.
2) There is also a need to optimize the overall biogas plant efficiency either from biogas generation or utilization pathway. This includes to utilise by-products from the biogas power plant such as heat generated from the gas engine which may improve overall utilization efficiencies of combined heat and power. Studies looking into potential utilization of CO_2 derived as by-product from biogas upgrading process could also be carried out. The potential uses of recovered CO_2 are for microalgae cultivation and food and beverage (F&B) industry. The biogas plant efficiencies can be further improved by adopting latest-improved technology including to fully automise and digitalise the plant operation, monitoring and quality control via the Fourth Industrial Revolution (IR 4.0). All these approaches contribute to better economic and improved safety aspects towards smart biogas plant in palm oil mills.

3) To further improve and develop the existing Malaysian Standard and new standard associated to production, utilisation, specifications and safety of biogas and Bio-CNG.

4) Mapping of palm oil mills to the nearby interconnection points, the natural gas pipelines, industrial areas and villages without grid electricity could identify the potential mills with biogas energy generated for grid connection, Bio-CNG injection and supply points, and rural electrification programme. Identified potential mills via mapping exercise could be notified as well as approached by the RE developers for further business engagement. Actual potential database could be developed which represent more accurate actual potential status for each utilisation routes.

5.3 Knowledge Contribution

1. This study has developed a systematic procedure which can be used by mill operators to determine the feasibility of developing Bio-CNG plant in their respective plants (Figure 5.1).
2. Characterised typical bio-CNG properties that can be used as a base line value for Bio-CNG plant development.

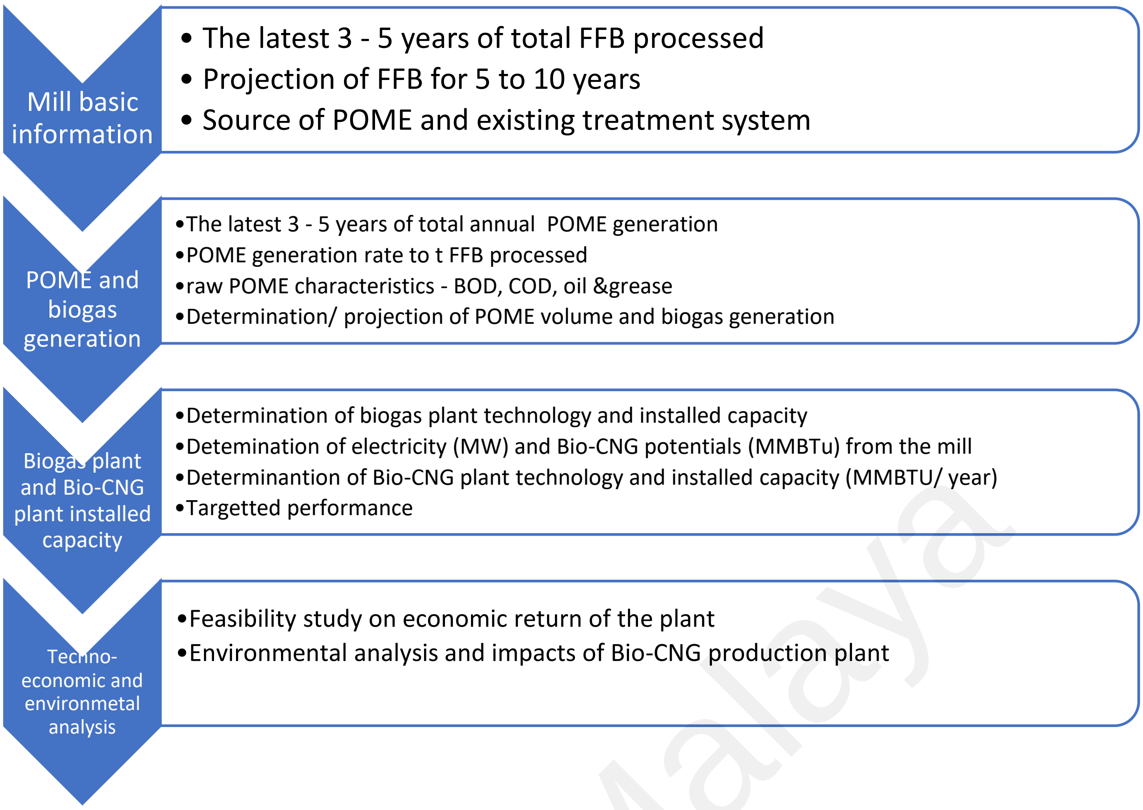

Figure 5.1: A systematic approach and procedure for the feasibility study of developing Bio-CNG production at a palm oil mill

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