ENERGY RECOVERY AND CARBON DIOXIDE EMISSION PERSPECTIVES OF ANAEROBIC DIGESTION OF PALM OIL MILL EFFLUENT

by

CHOU KIAN WENG

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LIST OF ABBREVIATIONS

ABR	Anaerobic Baffled Reactor
ACD	Anaerobic Contact Digester
AD	Anaerobic Digestion
AD-POME	Anaerobically digested POME
Ae- POME	Aerobically Treated POME
AHR	Anaerobic Hybrid Reactor
ABF	Anaerobic Baffled Filter
AN	Ammoniacal Nitrogen
APHA	American Public Health Association
AS	Activated Sludge System
ASR	Activated Sludge System with Sludge Recirculation
AUX	Auxiliary Energy Consumption
BOD	Biochemical Oxygen Demand
CAPEX	Capital Expenditure
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CPO	Crude Palm Oil
CSTR	Continuous Stirred Tank Reactor
DF	Dark Fermentation
DF-POME	Dark Fermented POME
DLs	Distribution Licensees

DO	Dissolved Oxygen
DOE	Department of Environment (Malaysia)
DS	Dissolved Solids
EFB	Empty Fruit Bunch
EGSB	Expended Granular Sludge Blanket
EPP	Entry Point Project
FFB	Fresh Fruit Bunch
FIAHs	Feed in Approval Holders
FID	Flame Ionization Detector
FiT	Feed in Tariff
GC	Gas Chromatography
GHG	Greenhouse Gases
GPS	Global Positioning System
HCB	Hydrogen Consuming Bacteria
HDPE	High Density Polyethylene
HPB	Hydrogen Producing Bacteria
HRT	Hydraulic Retention Time
LHV	Lower Heating Value
MAD	Mesophilic Anaerobic Digester
MDL	Method Detection Level
MF	Mesocarp Fiber
MLVSS	Mixed Liquor Volatile Suspended Solids
MQL	Minimum Quantification Level
MS	Mass Spectrometry
NKEA	National Key Economic Area

NRB	Nitrate Reducing Bacteria
O & G	Oil and Grease
OLR	Organic Loading Rate
OPEX	Operational Expenditure
PEG	Polyethylene Glycol
PKS	Palm Kernel Shell
POM	Palm Oil Mill
POME	Palm Oil Mill Effluent
RABR	Reversible Flow Anaerobic Baffled Reactor
RAD	Anaerobic Digester operated at Room Temperature
RCF	Relative Centrifugal Force
RSD	Relative Standard Deviation
SCSTR	Semi-Continuous Stirred Tank Reactor
SD	Standard Deviation
SEDA	Sustainable Energy Development Authority
SRB	Sulphate Reducing Bacteria
SS	Suspended Solids
SSV	Settled Sludge Volume
SVI	Sludge Volume Index
TA	Total Alkalinity
TACD	Thermophilic Anaerobic Contact Digester
TAD	Thermophilic Anaerobic Digester
TCD	Thermal Conductivity Detector
TDF	Thermophilic Dark Fermenter
TKN	Total Kjeldahl Nitrogen

TN	Total Nitrogen
TNB	Tenaga National Berhad
TS	Total Solids
TSS	Total Suspended Solids
TVFA	Total Volatile Fatty Acid
TVS	Total Volatile Solids
UASB	Up-flow Anaerobic Sludge Blanket
UASFF	Up-flow Anaerobic Fixed Film Reactor
UNFCCC	United Nations Framework Convention on Climate Change
VFA	Volatile Fatty Acid
VS	Volatile Solids
VSS	Volatile Suspended Solids

LIST OF SYMBOLS

µL	Microliter
Al	Aluminium
As	Arsenic
B	Boron
Ca	Calcium
$CaCO_3$	Calcium Carbonate
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
d	Day
Fe	Iron
GJ	Gigajoule
H^+	Hydrogen Ion
H_2S	Hydrogen Sulfide
ha	Hectare
K	Potassium
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt Hour
Mg	Magnesium
MJ	Megajoule
mL	Milliliter

mM	Millimole
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Natrium
$NaCO_3$	Natrium Carbonate
$NaHCO_3$	Natrium Bicarbonate
NaOH	Natrium Hydroxide
NH_3	Ammonia
Ni	Nickel
NTU	Nephelometric Turbidity Unit
P	Phosphorus
Pb	Lead
ppm	Parts per Million
Pt-Co	Platinum-Cobalt Unit of Colour
R	Sludge Recirculation Ratio
RM	Ringgit Malaysia
S	Sulfur
Se	Selenium
Yr	Year
Zn	Zinc

PERSPEKTIF PEMEROLEHAN SEMULA TENAGA DAN PELEPASAN KARBON DIOKSIDA DARIPADA PENCERNAAN ANAEROBIK EFFLUEN KILANG KELAPA SAWIT

ABSTRAK

Kajian ini bertujuan untuk menilai prestasi pencernaan anaerobik (AD) secara dua peringkat untuk POME diikuti pasca olahan aerobik. AD secara satu peringkat berperanan sebagai bandingan untuk AD secara dua peringkat. Penilaian terhadap AD bertumpu pada penghasilan biogas dan kecekapan olahan. Penilaian terhadap pasca olahan aerobik bertumpu pada kecekapan olahan dan kualiti efluen akhir. Pencerna anaerobik berskala makmal digunakan untuk membina AD secara satu peringkat kemudian diubahsuaikan menjadi AD secara dua peringkat. Bioreaktor berskala makmal digunakan sebagai sistem enapcemar teraktif (AS) kemudian diubahsuaikan menjadi sistem enapcemar teraktif dengan kitaran enapcemar (ASR) untuk pasca olahan aerobik. Keputusan eksperimen terbaik digunakan untuk menganggarkan hasil tenaga, pelepasan CO_2, dan pengurangan pelepasan CO_2 dari sistem olahan POME yang disimulasi. AD POME secara satu peringkat yang menggunakan pencerna anaerobik kontak termofilik (TACD) yang beroperasi pada 55 °C dan masa tahanan hidraulik (HRT) pada 10.00 hari menunjukkan kadar penghasilan metana (CH_4) 0.385 L/g COD_{degrad} dan 24.191 L/L POME. Ini bersamaan dengan 781.42 MJ/m^3 POME. Penguraian COD dan TSS bagi proses tersebut mencapai 83.9 dan 63.2 %, masing-masing. Kepekatan COD, BOD_3, dan TSS dalam efluen terakhir adalah 789, 19, dan 108 mg/L, masing-masing. Warna ketara, warna kelihatan dan kekeruhan efluent akhir adalah 4835 dan 5888 Pt-Co dan 41 NTU, masing-masing. AD POME secara dua peringkat dalam keadaan penapaian gelap termofilik (TDF) dan TACD yang beroperasi pada 55 °C dan HRT 10.00 hari menunjukkan kadar penghasilan H_2 sebanyak 0.314 L/g COD_{degrad} dan 1.714 L/L POME dan kadar penghasilan CH_4 sebanyak 0.397 L/g COD_{degrad} dan 23.230 L/L POME. Ini bersamaan dengan 765.29 MJ/m^3 POME. Penguraian COD dan TSS bagi proces tersebut mencapai 80.8 dan 64.4 %, masing-masing. Kepekatan COD, BOD_3, dan TSS dalam efluen terakhir adalah 873, 20, dan 205 mg/L, masing-masing. Warna ketara, warna kelihatan dan kekeruhan efluen akhir adalah 4915 dan 6558 Pt-Co dan 79 NTU, masing-masing. AD secara dua peringkat tidak menunjukkan kelebihan yang ketara berbanding dengan AD secara satu peringkat dalam pemulihan tenaga, kecekapan olahan dan pelepasan CO_2. Pasca olahan aerobik yang menggunakan ASR menunjukkan kualiti efluen akhir yang dapat mematuhi had pelepasan (BOD_3 dan TSS) yang disenaraikan dalam Jadual Kedua, Peraturan 12 (2) dan 12 (3), Peraturan-perautran Kualiti Alam Sekeliling (Pelesenan) 1977. Berdasarkan anggaran kajian simulasi, biogas yang dihasilkan di kilang kelapa sawit berkapasiti operasi 60 tan/jam dapat menjanakan 13503023 kWh/tahun untuk dijual serta meningkatkan keuntungannya sebanyak 5.99 – 15.48 %. Penggantian terhadap sistem olahan kolam terbuka konvensional dengan pencerna anaerobik yang tertutup dapat mencapai pengurangan pelepasan CO_2 sebanyak 99.83 %, bersamaan dengan 47799 tan/tahun. Jumlah pengurangan pelepasan CO_2 (termasuk penjanaan elektrik) mencapai 57170 tan/tahun.

ENERGY RECOVERY AND CARBON DIOXIDE EMISSION PERSPECTIVES OF ANAEROBIC DIGESTION OF PALM OIL MILL EFFLUENT

ABSTRACT

This study aims to evaluate the performance of two-stage anaerobic digestion (AD) of POME with aerobic post-treatment. The single-stage AD served as a comparison for the two-stage AD. Evaluation on the AD was mainly focused on biogas production and treatment efficiency whereas the evaluation on aerobic post-treatment was emphasized on treatment efficiency and final effluent quality. Laboratory scale anaerobic digester was used to develop single-stage AD then modified into a two-stage AD. Laboratory scale bioreactors were used as activated sludge system (AS) then modified into activated sludge system with sludge recirculation (ASR) for aerobic post-treatment. The best experimental results were used to estimate the energy yield, CO_2 emission, and CO_2 emission reduction from a simulated POME treatment system. The single-stage AD of POME using a thermophilic anaerobic contact digester (TACD) which operated at 55 °C and hydraulic retention time (HRT) of 10.00 days demonstrated methane (CH_4) yield of 0.385 L/g $COD_{degraded}$ with a production rate of up to 24.191 L/L POME which equivalent to 781.42 MJ/m^3 POME. The corresponding COD and TSS degradation were 83.9 and 63.2 %, respectively. The COD, BOD_3, and TSS concentration of the final effluent were 789, 19, and 108 mg/L, respectively; whereas the true colour, apparent colour and turbidity was 4835 and 5888 Pt-Co and 41 NTU, respectively. The two-stage AD of POME using a thermophilic dark fermenter and a thermophilic anaerobic contact digester (TACD) which operated at 55 °C and hydraulic retention time (HRT) of 10.00 days demonstrated hydrogen (H_2)

yield of 0.314 L/g $COD_{degraded}$ and a production rate of 1.714 L/L POME and CH_4 yield of 0.397 L/$COD_{degraded}$ and a production rate of 23.230 L/L POME, equivalent to 765.29 MJ/m^3 POME. The corresponding COD and TSS degradation was 80.8 and 64.4 %, respectively. The COD, BOD_3, and TSS concentration of the final effluent were 873, 20, and 205 mg/L, respectively; whereas the true colour, apparent colour and turbidity was 4915 and 6558 Pt-Co and 79 NTU, respectively. The two-stage AD shows no significant advantages over the single-stage AD, in energy recovery, treatment efficiency and CO_2 emission. The aerobic post-treatment using ASR shows the final effluent quality could comply with discharge limit (BOD_3 and TSS) listed in Second Schedule, Regulation 12 (2) and 12 (3), Environmental Quality (Prescribed Premises) Regulations 1977. Based on estimation, the biogas produced from a palm oil mill with an operating capacity of 60 ton/h could generate 13503023 kWh/yr for sales to gain 5.99 – 15.48 % of extra profit. Replacement of the conventional open ponding system with a closed anaerobic digester could achieve a CO_2 emission reduction of 99.83 %, equivalent to 47799 ton/yr. The total CO_2 emission reduction (including electricity generation) was 57170 ton/yr.

CHAPTER 1 INTRODUCTION

1.1 Malaysian Palm Oil Industry

The world crude palm oil (CPO) production is dominated by two Southeast Asian countries – Indonesia and Malaysia. Together, these two countries account for around 85 to 90 % of total global palm oil production (Indonesia-Investments, 2017). Figure 1 illustrates the CPO production of Indonesia and Malaysia from 2007 to 2015. The crop's full potential has been exploited and developed into a multi-billion Ringgit industry. The high production of CPO prompts the palm oil industry to become a backbone of the country’s economy. For example, palm oil export revenue achieved RM43.37 billion in the year 2016. Whereas the export of oil palm products, consisting of palm oil, palm kernel oil, palm kernel cake, oleo-chemicals, biodiesel and finished products have achieved total export earnings of RM 64.58 billion (MPOB, 2017a).

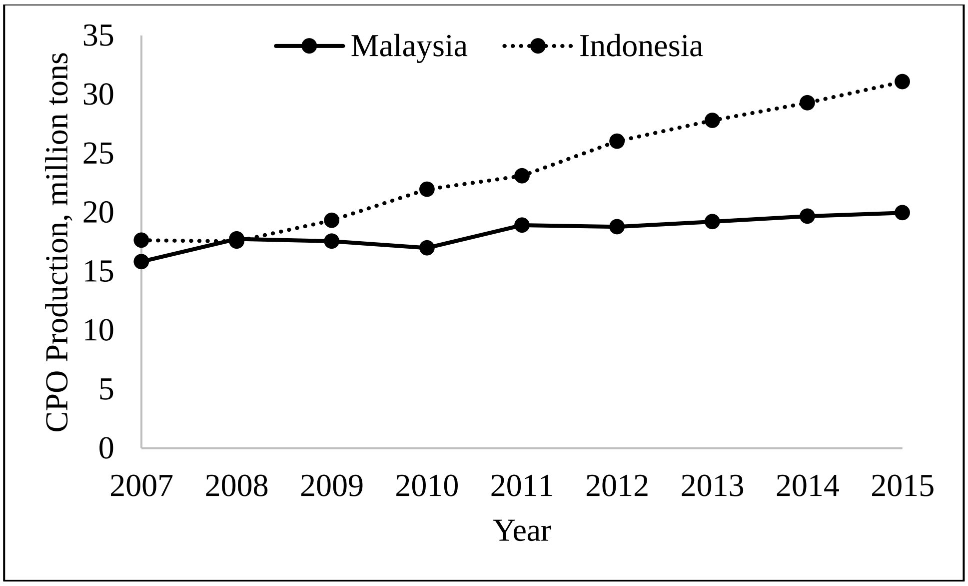

Figure 1.1 CPO production in Indonesia and Malaysia, 2007 – 2015 (Directorate General of Estate Crops & Agriculture, 2016; MPOB, 2017b).

1.2 Palm Oil Mill Effluent (POME) and Related Environmental Issues

Up to the year 2016, the number of in-operation palm oil mills (POM) in Malaysia was recorded as 445, with a total capacity of 110.326 million ton fresh fruit bunch (FFB) per year (MPOB, 2017b). These mills processed 85.836 million ton of FFB to produce 17.319 ton of CPO. The massive production of CPO using wet palm oil milling process, the most standard and typical way of extracting CPO (Wu et al., 2010), have resulted in the larger amount of palm oil mill effluent (POME). POME will threaten the environment if discharged to the watercourse without proper treatment. Generally, palm oil mills (POMs) are located close to rivers from which the river water will be extracted for their milling activities (DOE, 1999). The discharge of partially treated effluent into the rivers was the simplest way of POME disposal. However, excessive quantities of partially treated POME will severely deplete the dissolved oxygen (DO) of a watercourse and suffocate the aquatic ecosystem. The greenhouse gases (GHG) emission, methane (CH_4) from conventional POME treatment system caused detrimental effect to the environment due to its global warming potential is 25 times compared to carbon dioxide (CO_2) (Chin et al., 2013).

1.3 Problem Statement

The current issues and problems existing in POME treatment were identified from literature reports and summarized in the following subsections. The brief descriptions guided the present study, which is necessary and potentially valuable to the discipline.

1.3.1 Anaerobic and Aerobic Treatment of POME

According to previous review report (Ahmed et al., 2015; Wu et al., 2010), sporadic research has been conducted to approach a solution for POME treatment. Different kinds of wastewater treatment technologies recognized has been attempted to apply in POME treatment such as anaerobic digestion (AD), aerobic treatment, physicochemical treatment and membrane separation processes (Ahmed et al., 2015). AD is the most suitable and effective treatment for high organic strength wastewater such as POME. It is a multistage (hydrolysis, acidogenesis, acetogenesis and methanogenesis) degradation of organic matters and transformed into CH_4 and CO_2 by the biological reactions of a microbial consortium. To meet local regulatory limits, an appropriate post-treatment before discharging is necessary because the anaerobically digested (AD-POME) still contains a high amount of biodegradable substances and suspended solids.

Application of AD as primary treatment of POME then followed by aerobic post-treatment appears to be the most techno-economical practical approach (Chan et al., 2010a). However, there is insufficient research discuss the combination of different POME treatment systems because most of the current studies were discrete research that focuses on an individual treatment process. In fact, it is difficult to obtain satisfactory treatment by a physical, chemical or biological method alone on a commercial scale due to the unique characteristic of POME as high organic, highly coloured and the existence of recalcitrant compounds (Liew et al., 2015).

Two-stage AD finalized to the combined biogas production of hydrogen (H_2) in the first phase reactor and CH_4 in the subsequent phase reactor has gained interest among the researchers (F. Micolucci et al., 2014). H_2 is a promising energy carrier in the future because it has a higher energy density and a lower pollutants generation compared with CH_4. Consequently, the encouraging results from recent studies have gained increasing attention of researchers, especially those from palm oil producing countries such as Indonesia, Malaysia, Thailand, etc.

Yet, the advantages of two-stage over single-stage AD of POME remains unclear because there is limited literature reported and compared both systems that operated under similar conditions. For example, current published work only presents the treatment efficiency and biogas production of a two-stage AD of POME without making a comparison with a single-stage AD that working at similar operational conditions. In fact, previous research on the AD of POME demonstrated the application of different anaerobic bioreactors at varied operational conditions (Wu et al., 2010). These further hinder the comparison between single-stage and two-stage AD of POME. Thus, more investigation on evaluation and comparison between single-stage and two-stage AD of POME at similar treatment conditions is necessary.

There is very limited literature resource demonstrated comprehensive results of the aerobic post-treatment of AD-POME. Previously, the laboratory scale sequencing batch reactor (SBR) was applied to investigate the aerobic treatment of AD-POME collected from local POM (Chan et al., 2010a). The experimental results show the activated sludge system could be a viable secondary treatment system for complete compliance with the local discharge limit. Generally, the treatment efficiency of a secondary treatment system is dependent on the primary treatment system. As most organic pollutants degraded in the primary treatment system, the organic loading of AD-POME into secondary treatment system will be lowered. Hence, the overall treatment efficiency could be improved. Nevertheless, there is insufficient research investigate and compare the aerobic post-treatment of AD-POME from single-stage and two-stage AD. The effect of different AD-POME on aerobic post-treatment remains unclear and more attention is needed to fill this research gap.

1.3.2 Conditioning of Feeding Substrate and Anaerobic Sludge

Large-scale field study usually provides the best approximation of full-scale performance because it also estimates the environmental impact and cost with a higher level of certainty (Rawe et al., 1993). However, most of the published research on the AD of POME (Wu et al., 2010; Ohimain & Izah, 2017) involved the application of laboratory scale experiment because it is easier to control and more cost-effective. These treatability studies mainly focused on the process optimization and performance evaluation. The substrate pretreatments and chemical additions were observed in recent laboratory research which demonstrated biogas production from the AD of POME. Recent studies have investigated the effect of various organic loading rate (OLR) on biohythane production and degradation of POME using two-stage AD (Krishnan et al., 2016b; Krishnan et al., 2017). These studies demonstrated UASB-CSTR which operated at thermophilic temperatures could achieve high OLR of up to 125 kg COD/m^3.d. Based on information available from the literature, the feeding substrate for the experiments was diluted to different COD concentration. Furthermore, some physical pretreatment such as pre-settling, removal of suspended solid and oil also applied on POME for the experimental study (Najafpour et al., 2006; Fang et al., 2011; Choi et al., 2013).

Generally, both acidogenic and methanogenic microorganisms have their optimal working pH (Y. Chen et al., 2008). The well accepted optimal pH for biohydrogen production is 5.5 although it may vary slightly depending on the feeding substrate and the composition of the microbial population (Sivagurunathan et al., 2016). Whereas a pH value near to neutral conditions with high alkalinity is required for optimal biomethane production (Gerardi, 2003). POME is acidic in nature with pH ranged from 4.3 to 4.7 (Choorit & Wisarnwan, 2007; Fang et al., 2011; Poh & Chong, 2014) due to the presence of volatile fatty acids. Thus, alkali such as $CaCO_3$, $NaHCO_3$ and NaOH have been used to adjust the pH and alkalinity in single-stage and two-stage AD of POME (Najafpour et al., 2006; Choi et al., 2013; Mamimin et al., 2015; Krishnan et al., 2016b; Krishnan et al., 2017). Yet, the corresponding dosage of alkali required for pH adjustment has not been determined.

Supply of macro- and micronutrient supplements has become an important topic because the lack of certain nutrients has been identified to be the main reason behind poor process performance in agro-industrial biogas mono-digestion plants (Romero-Güiza et al., 2016). Recently, researchers have modified the macronutrients balance by adjusting the C:N:P of POME to the desired ratio using peptone, KH_2PO_4, NH_4Cl and Na_2HPO_4 solutions (Najafpour et al., 2006; Mamimin et al., 2015; Krishnan et al., 2016a; Krishnan et al., 2016b; Krishnan et al., 2017). Adding stimulatory concentration of metals, as micronutrients, to the feeding substrate has been found to increase biogas production and process performance (Ward et al., 2008). These micronutrients are crucial cofactors in numerous enzymatic reactions involved in the biochemistry of methane formation (Romero-Güiza et al., 2016). For the same purpose, some investigations of AD were conducted with supplementation of Fe, Ni and Co in POME (Bambang et al., 2012; Mamimin et al., 2015; Krishnan et al., 2016a; Krishnan et al., 2016b).

Besides that, varied anaerobic sludges have been inoculated to initialize AD of POME, including sludge from drainage channel bed, digested sludge from a food cannery industry and animal manure (Najafpour et al., 2006). Anaerobic sludge from the existing full-scale POME treatment system was a better choice of inoculation source (Krishnan et al., 2016b; O-Thong et al., 2016). It greatly reduces the acclimatization period since the indigenous microorganisms within the anaerobic sludge have been well-adapted to POME. Moreover, the anaerobic inoculum has been enriched by adding synthetic medium (O-Thong et al., 2009) or heat-treated at 90 to 100 °C for 60 min to enrich indigenous H_2 producing bacteria and inhibit methanogens (Krishnan et al., 2016a; Krishnan et al., 2016b; Krishnan et al., 2017). However, the research found that there are no differences in H_2 production were observed by different pretreatments on anaerobic sludge and untreated sludge after long-term continuous operation (Luo et al., 2010). Thus, the effectiveness of anaerobic inoculum enrichment by pretreatment remains questionable.

Overall, the practices of substrate pretreatments, chemicals, and nutrients additions may significantly be altered the physicochemical characteristics of the feeding substrate (POME). Consequently, the experimental results could be misinterpreted because it may not represent the actual process efficiency. Although the above-mentioned practices are sometimes effective, it comes at a cost monetary, technical and energy that often impractical or operationally incompatible with actual full-scale POME treatment system. For example, it is impractical to dilute POME for treatment since this will expand operating capacity of the industrial scale treatment system. Thus, there appears to be a knowledge gap between laboratory-scale research and full-scale application, because the obtained experimental results are over-optimistic to estimate the efficiency of a full-scale AD system of the technology under study. In fact, for applied research in the AD of POME, researchers should consider and emphasize the practicability of applied technology by striving to simulate the conditions that may encounter during full-scale application.

1.3.3 Profit, Energy Yield and Carbon Dioxide (CO_2) Emissions

In the year 2014, Malaysian Government imposed mandatory installation of biogas trapping or CH_4 avoidance facilities in new POMs and mills that applying for capacity expansion to reduce greenhouse gas emissions (BorneoPost, 2014). The 5th Entry Point Project (EPP) in the palm oil National Key Economic Area (NKEA) also aims to achieve the installation of biogas facilities in all POMs in Malaysia by 2020 (MPOB, 2014a). Hence, there is an increasing number of POM applied various techniques to capture biogas for flaring or generate heat and electricity. The mainstream attention on the AD is shifted from wastewater treatment to cost-effective production of bioenergy (Lv et al., 2010). Recently, some researchers have calculated the amount of bioenergy recovered from the AD of POME (Mamimin et al., 2015; Krishnan et al., 2016a; O-Thong et al., 2016). However, few investigations included a cost analysis of installing full-scale AD system for POME treatment. In fact, private sectors only will make considerable investments after recognizing the cost-effective value of upgrading the existing treatment system to high-efficiency AD system.

Generally, one of the most economical ways to capture biogas from existing conventional open ponding in POM is to cover it with high-density polyethylene (HDPE) geomembrane. Nevertheless, Chin et al. (2013) observed that on average, closed anaerobic digester tanks have better performance compared to the covered anaerobic ponds. Consequently, low CH_4 production from these ponds encouraging flaring of biogas instead of bioenergy generation. This is a waste of bioenergy although flaring the biogas also reduce the greenhouse gases (GHG) effects (Chin et al., 2013). Thus, future research such as energy yield and economic balance is necessary to evaluate the implementation potential of bioenergy production from the AD of POME.

The hazard impact of CH_4 is more than 25 times greater than CO_2 over a 100-year period because CH_4 is more efficient at trapping radiation than CO_2 (USEPA, 2017). The recovery of energy from biogas greatly reduce greenhouse gases emission, in CO_2 equivalent, by avoiding the direct release of CH_4 into the atmosphere. However, CO_2 emission only can be reduced but not eliminated from the corresponding processes. There are two main sources of CO_2 emission in AD with biogas recovery. AD contributed to CO_2 emission because biogas contains a significant amount of CO_2 in which the concentration varied depends on the type of organic matters degraded. Generally, direct combustion of biogas is the most common technique to obtain energy in term of heat. Combustion of CH_4 is another source of CO_2 emission. Despite the energy yield efficiency is an important factor in choosing anaerobic treatment technology, CO_2 emission should be considered when choosing environmental friendly processes. The information regarding the CO_2 emission in single-stage and two-stage AD of POME is limited. Thus, the corresponding assessment of CO_2 emission is needed for ease of comparison.

1.4 Research Questions

Five research questions were derived from the above problem statement and need to be addressed in this study, as follows:

i. How good is two-stage AD compared to a single-stage AD of POME?

ii. Will the difference in AD of POME affect the aerobic post-treatment?

iii. How much can biogas yield, CO_2 emission, and CO_2 emission reduction be obtained from AD of POME?

iv. How profitable is the POM that implement biogas plant?

1.5 Research Objectives

To answer the research questions, this study aims to evaluate the performance efficiency of two-stage anaerobic digestion (AD) of palm oil mill effluent (POME) with aerobic post-treatment.

The specific objectives of this research are:

i. To compare single-stage and two-stage AD of POME in treatment efficiency, biogas production, energy yield as well as carbon dioxide (CO_2) emission factor;
ii. To evaluate the treatment efficiency of aerobic post-treatment of single-stage and two-stage AD of POME;
iii. To estimate the energy yield, CO_2 emission, and CO_2 emission reduction of a simulated palm oil mill (POM) based on the best obtained experimental results.
iv. To estimate the potential profit from biogas plant in POM.

For practical consideration, the experimental study was designed to fulfill the following criteria:

i. using undiluted feeding substrate to preserve the original physicochemical characteristics of POME;
ii. avoid any chemicals or nutrients addition during the entire experimental period, and
iii. using mixed culture originated from an existing POME treatment system.

1.6 Scope of Study

This research is divided into two parts: a) a laboratory scale experimental study and b) a simulation study of a POME treatment system with biogas recovery. The laboratory scale experimental study was designed to achieve objective i), ii) and iii) focus on the application of AD as primary treatment of POME while aerobic degradation as post-treatment for AD-POME. The experiments involve a series of system modification, from single-stage AD to two-stage AD, as well as from activated sludge system (AS) to activated sludge system with sludge recirculation (ASR), after evaluating the performance of the previous treatment system.

After that, a simulation study was designed to achieve objective iv) and v) as aforementioned. The simulation study was intended to estimate the energy yield, potential profit, CO_2 emission, and CO_2 emission reduction from a POME biogas plant. In doing so, the operating conditions of POME biogas plant of a typical POM is simulated based on the data and information collected from published literature and the best experimental results.

1.7 Novelty of Research

Current literature often applied varied inoculum enrichment methods as well as adding foreign microbial source, either pure or mixed culture, to enhance the AD process efficiency. These techniques may interrupt the existing microbial communities in the AD then affect the process efficiency of the downstream treatment (aerobic post-treatment). To avoid the above problem, this study applied indigenous microorganisms from the existing industrial-scale POME treatment system to initiate AD and aerobic post-treatment. The application of these indigenous microorganisms eases to achieve dynamic stability of microbial communities in the AD and aerobic post-treatment.

This research also applied in-situ resource utilization to improve the treatment efficiency of an AD of POME and aerobic post-treatment of AD-POME without chemicals and nutrients supplement. The experiments were planned to stimulate the performance of AD with aerobic post-treatment by recirculates a portion of the sludge (in-situ resource) back to the processes to retain sufficient concentration of active biomass. The experimental results are expected to be more representative than current literature data to demonstrate the actual treatment efficiency of the processes because supplement of chemicals and nutrients are not common in industrial scale POME treatment plant.

Energy production is the primary advantages of AD compared to other wastewater treatment technologies; while reducing CO_2 emission is the environmental challenge to prevent global warming getting out of hand. Yet, assessment of energy production and CO_2 emission from single-stage and two-stage AD of POME are not within the mainstream research objectives. Thus, this research investigated the energy production and CO_2 emission from single-stage and two-stage AD to compare the effectiveness of these processes.

CHAPTER 2 LITERATURE REVIEW

2.1 POME and Regulatory Standards

Figure 2.1 shows the common processes involved in the conventional crude palm oil production and the source of POME (Chou, 2011). The typical POM processes were previously described in Industrial Processes & The Environment – Crude Palm Oil Industry (DOE, 1999) therefore only summarized in Appendix A. This process requires about 1.5 m^3 of water for each ton of FFB where 50 % of the water results in palm oil mill effluent and the rest being lost as steam, mainly through sterilizer, piping leakages, as well as wash waters for tankers (DOE, 1999). The water is typically obtained from the nearby freshwater resources, i.e., the rivers, which incurs very little treatment and pumping costs (Liew et al., 2015).

Basically, there are three main sources of POME, approximately 0.9 m^3 of sterilizer condensate, 1.5 m^3 of separator sludge and 0.1 m^3 of hydrocyclone wastewater per ton of CPO produced. Thus, approximately 2.5 m^3 of POME is generated per ton of CPO produced in a well-managed POM with good housekeeping practices. However, the national average is about 3.5 m^3 of POME per ton of CPO produced.

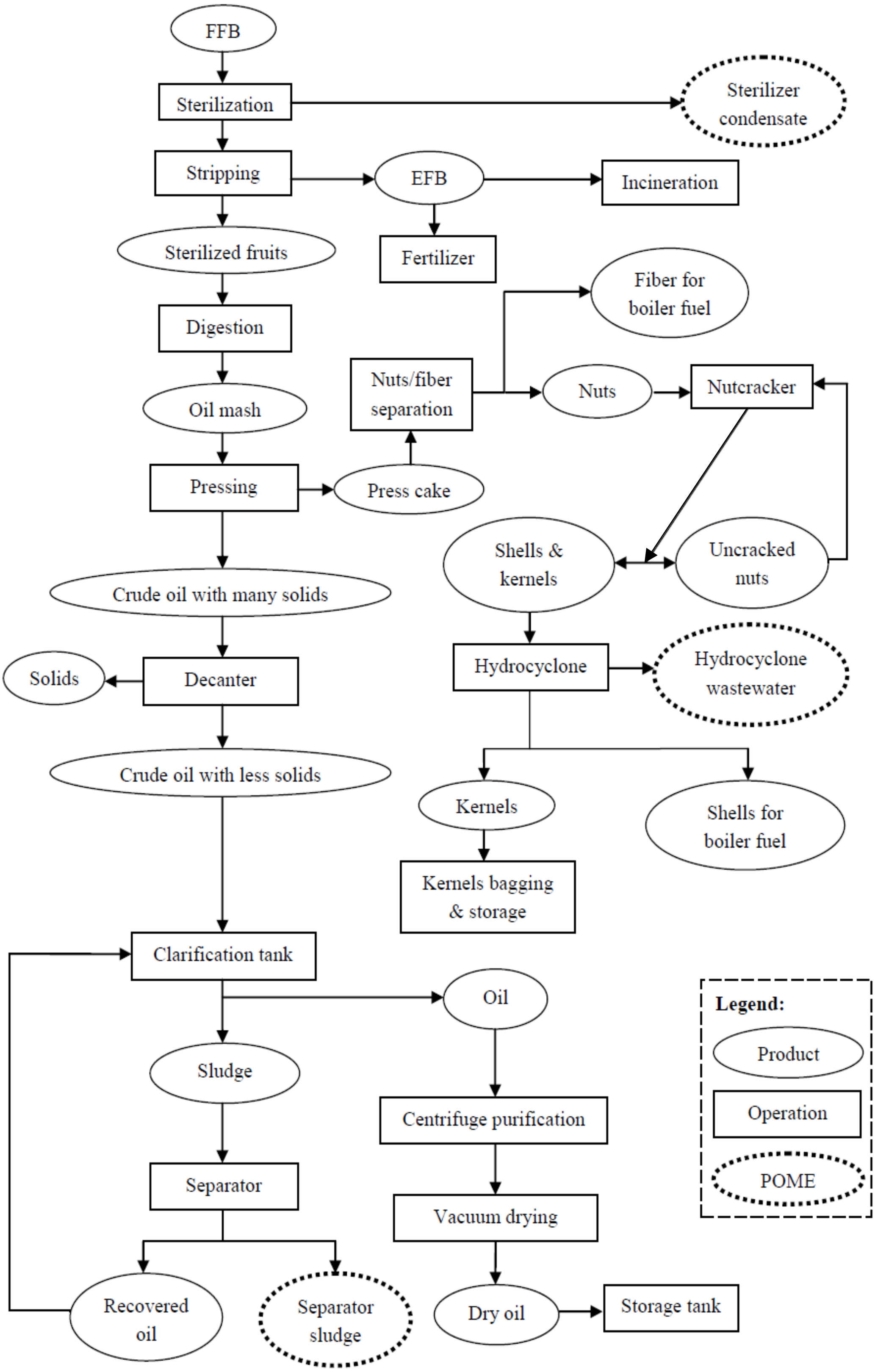

Figure 2.1 Conventional CPO extraction process.
Adapted from (Chou, 2011)

It is not astonishing that a massive generation of the POME has turned out to be the primary source of water pollution in the nearby area. POME is a thick brownish colloidal, a mixture of water and solids with a distinct offensive odour. About 2 – 3 % is suspended solids, which are mainly debris from palm mesocarp, and 0.7 % is residual oil (DOE, 1999). POME is hot, 80 to 90 °C due to the introduction of heat from sterilization and vigorous mechanical processes (Hassan et al., 2006). It is important to note that no chemicals are added in the oil extraction process, therefore, making POME non-toxic to the environment. But the direct discharge of POME into watercourses will make serious environmental problems due to its high organic strength is hundred times as polluting as domestic sewage (Ma and Augustine Ong, 1985).

Table 2.1 shows the typical quality characteristics of the individual wastewater. The sterilizer condensate contains fewer suspended solids together with numerous dissolved solids because the oil palm fruits are not yet smashed in the sterilization process. A major portion of pollutants originate from the clarification wastewater water is used to wash the sludge in the separator. Hydrocyclone wastewater only contributes 4 % of the total volume of POME and has the lowest organic strength among these wastewaters. However, the characteristics of POME vary widely and depend on the quality of palm fruits, processing techniques, quality control of individual mills, crop seasons and other factors (Yacob et al., 2006a; Poh & Chong, 2009; Wu et al., 2010; Liew et al., 2015). Thus, a reliable POME treatment system must have the operational capacity to withstand fluctuation of its wide-ranging composition.

Table 2.1 Typical characteristics of individual wastewater and POME.

Parameter	Sterilizer Condensate	Clarification Wastewater	Hydrocyclone Wastewater	POME
pH	5.0	4.5	-	4.2
O & G, mg/L	4000 – 4200	6900 – 7000	300	6000
BOD$_3$, mg/L	23000 – 23200	28700 – 29000	5000 – 5200	25000
COD, mg/L	47000 – 47200	63800 – 64000	14700 – 15000	50000
TS, mg/L	-	-	-	40500
TSS, mg/L	5000	23000 – 23300	7000 – 7800	18000
DS, mg/L	34000 – 36100	22000	100 – 400	-
TVS, mg/L	-	-	-	34000
AN, mg/L	20 – 22	40 – 48	-	35
TN, mg/L	500 – 600	1200	90 – 100	75
Generation, m^3/t CPO	0.9	1.5	0.1	2.5
% of POME	36	60	4	100

Source: (DOE, 1999; Hosseini & Abdul Wahid, 2015)

As shown in Table 2.2, POME still contains substantial quantities of valuable plant nutrients even after treatment. Generally, the nutrients are accumulated in a bottom slurry of AD-POME and aerobically digested POME. Its compositions will diverge depends on the treatment subjected.

Table 2.2 Typical nutrient composition of POME.

Type of POME	**BOD, mg/L**	**N, mg/L**	**P, mg/L**	**K, mg/L**	**Mg, mg/L**
Raw POME	25000	950	150	1960	345
AD-POME:					
Stirred tank	1300	900	120	1800	300
Supernatant	450	450	70	1200	280
Slurry	190	320	40	1495	260
Bottom slurry	1000 – 3000	3550	1180	2390	1510
Aerobically digested POME:					
Supernatant	100	50	12	2300	540
Bottom Slurry	150 – 300	1495	460	2380	1000

Source: (DOE, 1999)

Table 2.3 displays the available nutrients, equivalent to the fertilizer of ammonium sulphate, rock phosphate, muriates of potash, kieserite and limestone dust, from different types of POME. Land application of sludge can substantially cost saving by reducing the inorganic fertilizer requirement as well as recycling nutrients back to the ecosystem.

Table 2.3 Annual fertilizers equivalents of different types of POME.

Fertilizer	**Raw Effluent**		**Digested Effluent**		**Ditch Supernatant**	
	Amount, ton	**RM**	**Amount, ton**	**RM**	**Amount, ton**	**RM**
Ammonium Sulphate	761	266350	685	239750	343	120050
Rock Phosphate	292	71540	221	54271	71	17395
Muriate of Potash	713	249550	563	197050	375	131250
Kieserite	563	212814	446	168784	272	102816
Limestone Dust	220	11660	188	9994	98	5 194
Total	-	811914	-	669849	-	376705

Source: (MPOB, 2014b)

Instead of land application, discharge of treated POME into nearby watercourse is another choice to handle this wastewater. From 1965 to 1977, the daily discharge alone increased more than 300 % and the POM was considered the largest industrial source of organic pollution among the major pollution source by industry sectors (DOE, 1999; Ahmed et al., 2015). The Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977, promulgated under the enabling powers of Section 51 of the Environmental Quality Act 1974, were the first set of regulations for control of industrial pollution sources (DOE, 1999). Table 2.4 shows the POME discharge limit as in the Second Schedule, under Regulation 12 (2) and 12 (3). The main different of discharge limit compared to neighboring palm oil producing countries, is the exclusion of COD as one of the parameters after the year 1982. Contrary, Indonesia and Thailand still impose COD as one of the parameters of POME discharge standards with a concentration of 350 and 120 mg/L. Basically, the concentration of BOD in POME is the main problematic issue difficult in palm oil industry. When POME with high BOD concentration discharged to surface water, it may deplete the dissolved oxygen then kill the aquatic organisms. There is an attempt to impose a more stringent discharge limit, 20 mg/L BOD_3 which the scope to cover environmentally sensitive areas and those locations in close proximity to water intake points (Liew et al., 2015). Overall, the POME discharge standards in Indonesia and Thailand are more stringent than Malaysia.

Table 2.4 POME discharge standards in Malaysia, Indonesia, and Thailand.

Parameters[a]	**Limit of discharge**		
	Malaysia[a]	**Indonesia**[b]	**Thailand**[c]
BOD	100[d]	100[f]	20[f]
COD	-	350	120
Total solids	-	-	3000
Suspended solids	400	250	50
Oil and grease	50	25	5
Ammoniacal nitrogen	150[e]	-	-
Total nitrogen	200[e]	50	200[g]
pH	5.0 – 9.0	6.0 – 9.0	5.0 – 9.0
Temperature	45	-	40

[*] All parameters are in units of mg/L except for pH and temperature (° C).

[a] Environmental Quality Act 1974 (DOE, 1999)

[b] Lampiran III, Baku Mutu Air Limbah Bagi Usaha Dan/Atau Kegiatan Industri Minyak Sawit (KEMLH, 2014).

[c] The Enhancement and Conservation of the National Environmental Quality Act B.E.2535 (1992) (PCD, 1996; Chavalparit, 2006).

[d] BOD_3 – The sample for BOD analysis is incubated at 30 °C for 3 days.

[e] Values of filtered sample.

[f] BOD_5 – The sample for BOD analysis is incubated at 20 °C for 5 days.

[g] TKN – Total Kjeldahl Nitrogen

2.2 POME Treatments and Biogas Utilization

The following subchapters discuss the current POME treatment technologies, including the full-scale and laboratory scale system as well as the biogas utilization based on available literature resources.

2.2.1 Conventional Treatment – Open Ponding System

Open ponding system, a combination of anaerobic, aerobic and facultative treatment, is the common treatment system which has been adopted in local POMs to treat POME (Ma & Ong, 1985). Figure 2.2 illustrated the schematic diagram of a conventional open ponding system for POME. A typical ponding system usually operates at long HRT thus it needs a huge area of land to accommodate a series of ponds or lagoons of different functions to achieve the desired characteristic for discharge to meet the local standard. Basically, it is cheap and simple to construct, by excavating the earth and only a layer of clay lining is needed (Hassan et al., 2004). The system may be comprised of different facilities such as a de-oiling tank, holding/equalization ponds, acidification pond, anaerobic, facultative and algae (aerobic) ponds nevertheless the quantity and dimension of tanks/ponds vary according to the operating capacity of POM along with the area available for ponds. An effluent performance monitoring of a local POM (sampling location) listed in Table 2.5 demonstrates highly fluctuated treatment performance of an open ponding system at August 2013 even it is designed with a long retention time of 120 days.

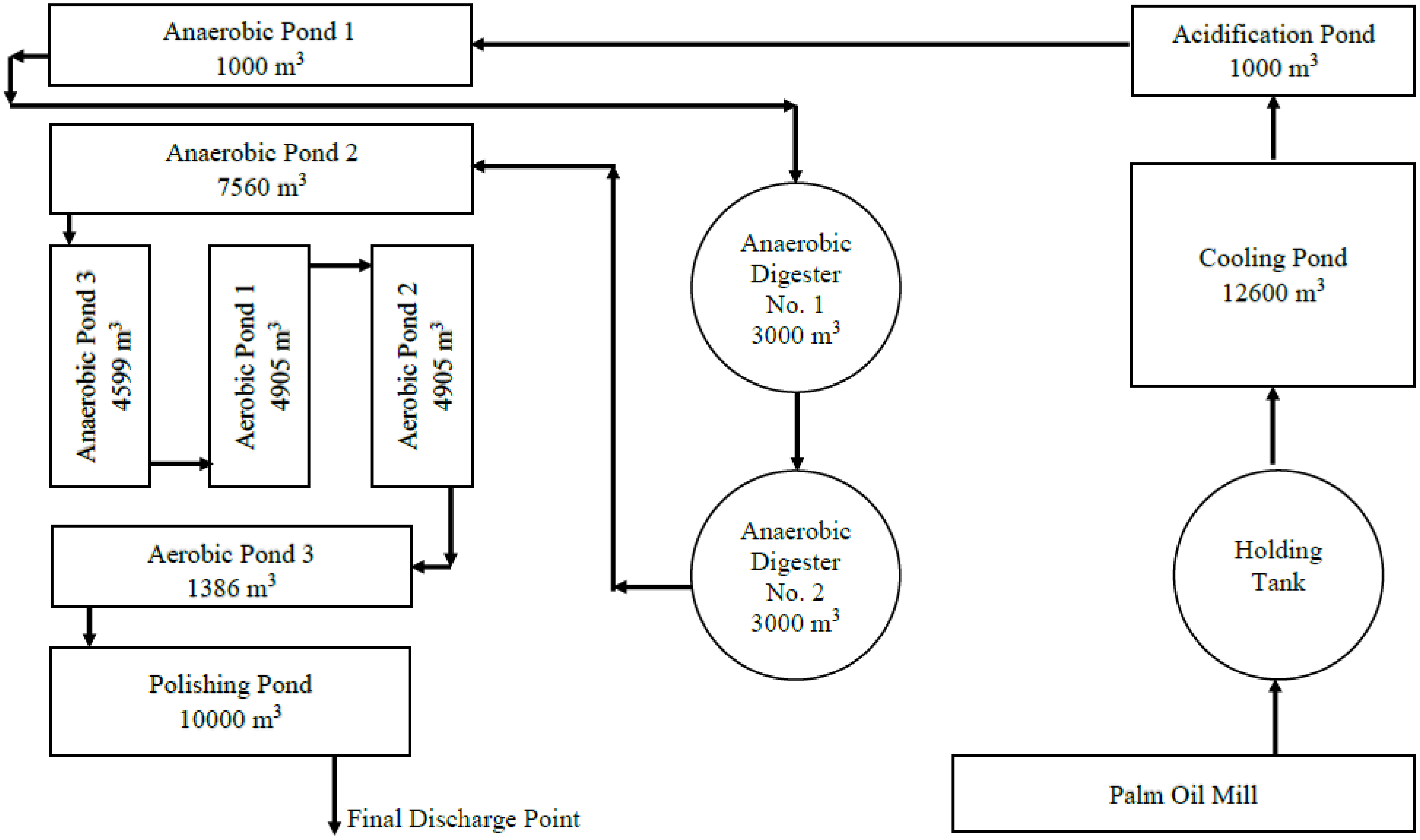

Figure 2.2 Schematic diagram of a conventional open ponding system for POME.

Table 2.5 Effluent performance monitoring of a POM.

Facilities	**Parameters**				
	HRT, days	**pH**	**DO, mg/L**	**COD, mg/L**	**BOD_3, mg/L**
Cooling pond	28	3.5 – 4.9	-	47682 – 95200	22020 – 44166
Acidification pond	2	3.5 – 4.9	-	-	-
Anaerobic pond 1	2	3.8 – 5.2	-	-	-
Anaerobic digester NO. 1	7	7.6 – 9.0	-	20800 – 64800	9660 – 30300
Anaerobic digester NO. 2	7	7.6 – 8.8	-	29120 – 46400	10585 – 20646
Anaerobic pond 2	17	6.3 – 8.2	-	-	-
Anaerobic pond 3	10	8.3 – 8.6	-	-	-
Aerobic pond 1	11	8.2 – 8.4	2.3 – 3.5	-	-
Aerobic pond 2	11	8.0 – 8.7	0.6 – 5.1	-	-
Aerobic pond 3	3	7.9 – 8.3	2.6 – 3.4	3680 – 25490	4500 – 10645
Polishing pond	22	-	-	267 – 1440	35 – 120

Source: (Malpom, 2013a)

Moreover, the biogas produced is not captured and released directly to the atmosphere. Previously, a long-term observation of CH_4 emission pattern from a commercial anaerobic pond system in Felda Serting Palm Oil Mill, Negeri Sembilan, was conducted based on the CH_4 composition and flow rate (Yacob et al., 2006a). The results showed that biogas flow rate ranged between 0.5 and 2.4 L/min/m^2 with CH_4 content between 35 and 70 % which influenced by the oil palm seasonal cropping and mill activities. This will cause serious air pollution because CH_4 has been categorized as one of the greenhouse gasses (GHG) with its global warming potential is 25 times compared to carbon dioxide (CO_2) (Chin et al., 2013). Furthermore, the operations and activities in POM also created offensive odour and caused a different degree of annoyance among the nearby public residents (Nurashikin et al., 2014). The research found that, in POM, the highest odour emission is from the anaerobic pond followed by the cooling pond and acidification pond (Yaacof et al., 2015). These issues need to be addressed immediately due to raising environmental awareness and public pressure.

2.2.2 Closed Anaerobic Treatment System

The palm oil producing countries have introduced some environmentally friendly policies and regulations to minimize the environmental impact of POME. For, example, Malaysian Palm Oil Board (MPOB) imposing the mandatory installation of biogas trapping or methane avoidance facilities in POMs as a condition for any new mill construction or existing mills applying for throughput expansion in the country (BorneoPost, 2014). Also, the Malaysian Government aims to achieve the installation of biogas facilities in all palm oil mills in Malaysia by 2020 (MPOB, 2014a). Thus, the open ponding systems will be gradually replaced by closed anaerobic treatment system.

The current anaerobic treatment technology of POME can be classified into two categories: i) covered anaerobic lagoon; and ii) closed anaerobic digester. The covered lagoon is an effective and reliable technology to capture biogas by installing covers which consist of synthetic high-density polyethylene (HDPE) geomembrane, over the existing anaerobic POME lagoons to create a simple anaerobic digester system. The covers are sealed by means of strip-to-strip welding and a peripheral anchor trench dug around the perimeter of the existing lagoon to ensure airtight coupling between all HDPE pieces. This covering approach effectively enables capture of nearly 100 % of the biogas produced in these lagoons to reduce odour and prevents CH_4 emissions to the atmosphere (UNFCCC, 2009c).

An economic analysis of biogas utilization has shown that the profitability of potential investment, in terms of internal rate of return (IRR), of a covered anaerobic lagoon was 16.1 %, which is higher than a closed anaerobic digester of 12.1 % (MPOB, 2014a). However, the average performance of the closed anaerobic digester tanks was better compared to the covered anaerobic ponds in terms of CH_4 production in the system (Chin et al., 2013). Chin and coworker (2013) concluded that the closed anaerobic digester tank was capable of generating up to 0.23 kg CH_4/kg COD treated while the highest CH_4 production of the covered anaerobic pond was only 0.16 kg CH_4/ kg COD treated (Chin et al., 2013). They suggested the corresponding observation was due to the lower efficiency of the covered anaerobic pond which lack of operational control and has long retention time for degradation. Thus, CH_4 generated from these ponds mostly were not utilized for energy generation but instead flared to the atmosphere.

Consequently, closed anaerobic digester has been installed in POM to improve CH_4 production. Varied types of closed anaerobic digester for POME treatment have been commercialized, including continuous stirred tank reactor (CSTR) (UNFCCC, 2007, 2008b, 2010c, 2010a, 2010b, 2011b, 2011a, 2012f, 2012l, 2013c, 2015b), plug-flow reactor (UNFCCC, 2013a), anaerobic baffled reactor (ABR) (UNFCCC, 2012k), up-flow sludge reactor (UNFCCC, 2012i), up-flow anaerobic sludge blanket (UASB) (UNFCCC, 2012f), anaerobic contact digester (ACD) (UNFCCC, 2012g), hybrid channel digester (HCD) (UNFCCC, 2012a), anaerobic hybrid reactor (AHR) and anaerobic plug-flow filter (APFF) (UNFCCC, 2013a) etc. The current commercialized POME AD technologies with biogas recovery in global top three CPO producing countries viz. Indonesia, Malaysia, and Thailand are listed in Table 2.6. Overall, the AD technologies of POME and biogas utilization in these countries were similar although different combinations may be applied which depends on varied operating conditions.

Table 2.6 Current commercialized industrial scale of POME AD technology and biogas utilization.

AD technology	Biogas utilization	Reference
Indonesia		
CSTR	Boiler	(UNFCCC, 2015b)
CSTR	Burner	(UNFCCC, 2010b)
AHR and APFF	Flaring system	(UNFCCC, 2013a)
ABR	Gas engine	(UNFCCC, 2012k)
Covered pond	Gas engine	(UNFCCC, 2013b)
Malaysia		
CSTR	Thermal heater	(UNFCCC, 2013c)
CSTR + UASB	Burner	(UNFCCC, 2012f)
Up-flow Sludge Reactor	Gas engine	(UNFCCC, 2012i)
Anaerobic Contact Digester	Gas engine	(UNFCCC, 2012g)
Covered pond	Boiler and gas engine	(UNFCCC, 2012e)
Covered pond	Gas engine	(UNFCCC, 2012d)
Thailand		
HCD	Gas engine	(UNFCCC, 2012a)
CSTR + UASB	Gas engine	(UNFCCC, 2011g)
Plug Flow - CSTR Based System	Gas engine	(UNFCCC, 2011e)
ABSR + UASB	Gas engine	(UNFCCC, 2011f)
Covered pond	Gas engine	(UNFCCC, 2009d)

Generally, the collected biogas could be used for on-site thermal energy and electricity generation. Figure 2.3 illustrated an industry scale of POME treatment system with biogas recovery. Literature shows remarkable biogas production rate from the large-scale AD of POME (Table 2.7), thus biogas could be an alternative fuel to replace biomass fuel and diesel (UNFCCC, 2013c). Mesocarp fiber (MF) and palm kernel shell (PKS) alone can supply more than enough electricity to meet the energy demand of a palm oil mill (POM) (Kole et al., 2012). However, the MF and PKS are valuable biomass fuels sold in the market for boilers (UNFCCC, 2011d). For example, PKS are in demand as biomass fuel for cement plants and brick kilns (UNFCCC, 2009a). Thus, after removing water condensate and desulfurization (MPOB, 2014a), the biogas captured will be displaced a part of the biomass fuel and combusted either