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Biogas Capture – A Means of Reducing Greenhouse Gas Emissions from Palm Oil Mill Effluent

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ABSTRACT

Oil palm – being the economic backbone of Malaysia – provides not just palm oil as the main commodity but also many other forms of by-products, namely oil palm trunks, fronds, palm kernel shell, mesocarp fiber, empty fruit bunches and palm oil mill effluent (POME), all of which can be transformed into value-added products for energy and non-energy uses. POME has been exploited as a renewable energy source under the Entry Point Project (EPP) 5 of the Palm Oil National Key Economic Area (NKEA), Economic Transformation Programme (ETP) since 2010. Implementation of EPP5 by building biogas trapping facilities at all palm oil mills across the country is one of the oil palm industry's renewable energy initiatives towards environmental sustainability. The production of biogas via anaerobic digestion of POME in the conventional treatment system releases ~65% methane into the atmosphere; methane is 25 times more potent than CO_2 as a greenhouse gas (GHG). Biogas capture and its various modes of utilisation, plus the more recently adopted methane avoidance from POME, have thus far progressed satisfactorily in lowering the carbon footprint of palm oil production. By fully harnessing biogas from POME, a projected GHG emissions of ~18 million tonnes CO_2eq per annum could be mitigated. This could greatly enhance the competitiveness of palm oil in facing more stringent sustainability requirements as stipulated under the EU Renewable Energy Directive and the USA EPA Renewable Fuel Standard 2 Program. The aim of this paper is to relate the Malaysian experiences in strategising and optimising POME management as well as biogas resource recovery, gearing towards accelerating sustainable palm oil production.

ABSTRAK

Industri sawit merupakan salah satu sumber ekonomi utama negara. Selain menghasilkan minyak sawit mentah sebagai sumber komoditi utama, ia turut menghasilkan produk sampingan seperti batang sawit, pelepah, tempurung, gentian mesokarpa, tandan buah kosong dan air kumbahan kilang sawit (POME). Kesemua sumber ini boleh digunakan bagi penghasilan produk nilai tambah sama ada untuk penggunaan berasaskan tenaga dan bukan tenaga. POME telah dikenalpasti dan digunakan sebagai sumber tenaga diperbaharui di bawah Projek Permulaan No. 5 (EPP5) – Bidang Ekonomi Utama Negara (NKEA), Program Transformasi Ekonomi Negara (ETP) sejak tahun 2010. Pelaksanaan EPP5 yang mensasarkan pembangunan loji pemerangkapan biogas di kilang sawit di seluruh negara merupakan salah satu inisiatif industri sawit negara ke arah pembangunan lestari dan mesra alam. Biogas yang terhasil daripada penguraian anaerobik ke atas POME dalam sistem rawatan kovensional membebaskan 65% gas metana ke atmosfera; metana berpotensi sebagai gas rumah hijau yang 25 kali lebih tinggi kesannya daripada gas karbon dioksida (CO_2). Pemerangkapan dan penggunaan biogas dengan pelbagai bentuk penjanaan tenaga, termasuklah perlaksanaan projek berasaskan pengelakan metana menggunakan POME, telah berkembang dengan baik bagi mengurangkan jejak karbon untuk penghasilan minyak sawit mentah. Dianggarkan sebanyak 18 juta tan CO_2eq setahun dapat dikurangkan sekiranya kesemua biogas yang dihasilkan di kilang sawit di seluruh negara diperangkap dan digunakan semula. Ini akan meningkatkan daya saing minyak sawit di peringkat global yang kini harus memenuhi pelbagai keperluan dan peraturan kemampanan yang ketat seperti yang termaktub di bawah program 'EU Renewable Energy Directive' dan 'USA EPA Renewable Fuel Standard 2'. Artikel ini membincangkan pengalaman Malaysia dalam usaha dan strategi mengoptimumkan pengurusan POME dan penggunaan sumber biogas ke arah memacu pembangunan mampan dalam penghasilan minyak sawit.

Keywords: palm oil mill effluent, greenhouse gas, renewable energy, sustainable development, industry initiative.

INTRODUCTION

Oil palm, *Elaeis guineensis* Jacq., is undeniably a golden crop for Malaysia as it produces not just the oil (only about 10% of the total biomass) as food source but a balance of 90% (Loh and Choo, 2013; Basiron and Chan, 2004) as a valuable lignocellulosic biomass with many different applications. The

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palm starts to bear fruit at the age of around three years, and has an economic life span of 25 years before being felled for replanting. The fresh fruit bunches (FFB) are harvested and transported to palm oil mills for oil extraction while the oil palm fronds and trunks are available during pruning and replanting.

After removing the fruit from FFB, empty fruit bunches (EFB) are left unutilised as they pile up in the mills, or are used as boiler fuel at the mills, or as soil mulch and fertiliser in the oil palm plantations. Palm oil comes from the mesocarp and palm kernel oil is extracted from the palm kernel. The by-products after oil extraction are mesocarp fiber, palm kernel shell and palm kernel cake. For every tonne of FFB processed in a mill, around 5.5% palm kernel shell, 13.5% mesocarp fibre and 22% EFB (all on a wet basis) are generated as solid waste materials (Loh, 2017; Liew *et al*., 2015; Kong *et al*., 2014; Ma, 1999; Chan *et al*., 1981). With an oil palm planted area of 5.74 million ha in 2016, this translates to about 70-80 million tonnes of solid oil palm biomass (dry weight basis) and 60-65 million tonnes of liquid wastewater (as palm oil mill effluent or POME) from the milling, pruning and replanting activities (*Table 1*).

POME CHARACTERISTICS AND POTENTIAL

POME is commonly treated in open ponding systems. It has high biological oxygen demand (BOD), chemical oxygen demand (COD) and suspended solids (SS) (*Table 2*). Hence, it is susceptible to natural microbial degradation. SS cause the inferior quality of the POME final discharge. The current limit of final discharge is 100 ppm BOD which most mills are able to comply with. However, recently the Department of Environment (DOE) has set a more stringent 20 ppm standard A BOD discharge limit which is difficult for most mills to comply with as current treatment technologies normally show inconsistent performance. As biogas is inevitably released during anaerobic digestion (AD) of POME, this gas should be captured and utilised, and possibly be integrated with any potential downstream tertiary treatment of POME as a move towards achieving the DOE requirement.

Through AD of POME in open ponding or in open digester tanks, biogas is released freely into the atmosphere. Biogas contains around 60%-70% CH_4, 30%-35% CO_2 and traces of H_2S (few hundred ppm to >2000 ppm) (Loh *et al*., 2013). Emission of biogas is undesirable as CH_4 is about 25 times more potent than CO_2 in warming the Earth, and is wasteful if not captured because biogas has high calorific value; and thus the energy released can be harnessed as a fuel. If all the mills (totaling 453 in 2016) (MPOB, 2016b) were to capture the released biogas, potentially 18 million tonnes CO_2eq yr^{-1} can be mitigated (Loh *et al*., 2017), and this is equivalent to a calculated life cycle GHG of 17.9 million tonnes CO_2eq (Vijaya *et al*., 2010). This huge volume of captured biogas translates to a total of 726 028 t CH_4 yr^{-1} which upon combustion with a thermal efficiency of 35% (Loh *et al*., 2014) produces about 480 MW of renewable electricity (*Table 3*).

TABLE 1. OIL PALM BIOMASS AVAIBILITY IN 2016 IN MALAYSIA

Type of oil palm biomass	Amount (million tonnes)		
	Wet basis	Dry basis	
Oil palm fronds (OPF) (from pruning activity*)	-	44.76	22.38**
OPF (from replanting activity)		1.23	0.61**
Oil palm trunks (replanting of 84 768 ha), MPOB (2016a)	-	6.31	3.16**
Empty fruit bunches (453 palm oil mills, fresh fruit bunches (FFB) processed = 85.837 mil t) (22% of FFB)	18.88	6.61	
Mesocarp fiber (13.5% of FFB)	11.59	6.95	
Palm kernel shell (5.5% of FFB)	4.72	4.01	
Palm oil mill effluent (POME) (~67% of FFB)	57.51 (1610 mil m^3 biogas)	2.88***	
Total		72.75	

Note: * Oil palm planted area: 5.738 million ha.
** 50% removal from the plantations.
*** 5% recovered solids (dry weight basis).

TABLE 2. CHARACTERISTICS OF PALM OIL MILL EFFLUENT (POME) AND DISCHARGE STANDARDS

Parameter	POME characteristics	Limit of POME final discharge		
		Since 1-1-1984	Standard A	Standard B
Temperature, °C	80 – 90	45	40	40
pH	3.3 – 5.7	5.0 – 9.0	6.0 – 9.0	5.5 – 9.0
BOD, mg $litre^{-1}$	18 000 – 25 000	100	20	50
COD, mg $litre^{-1}$	45 000 – 55 000	-	50	100
Suspended solids, mg $litre^{-1}$	25 000 – 31 000	400	50	100
Oil & grease, mg $litre^{-1}$	5 600 – 8 800	50	1/ND	10
Ammoniacal N, mg $litre^{-1}$	77 – 100	150*	10	20
Total N, mg $litre^{-1}$	670 – 780	200*	-	-

Note: *Value of filtered sample.
ND = Not Detectable.
Source: DOE (2009); Loh *et al*. (2013).

TABLE 3. POTENTIAL RENEWABLE ENERGY GENERATION FROM PALM OIL MILL EFFLUENT (POME) IN 2015

Material	Production rate	Quantity
Fresh fruit bunches (FFB)	-	97.57 million t
POME	0.65 m^3 t^{-1} FFB[a]	63.42 million m^3
Biogas[b]	28 m^3 m^{-3} of effluent	1776 million m^3
Total heat value	1 776 x 20 million MJ = 35 515 million MJ	35 515 million MJ = 9.87 million MWh[c]
Power output	35% of heat input	9.87 x 35% = 3.453 million MWh
Power plant size	Plant operates 300 d yr^{-1} = 7 200 h yr^{-1}	3 453 000/7 200 = 480 MW

Note: [a] Vijaya *et al*. (2008).
[b] Calorific value = 20 MJ m^{-3} at standard temperature and pressure (STP).
[c] 1 MJ = 1/3600 MWh.
Source: Loh *et al*. (2017).

Previously, this gained momentum under the Clean Development Mechanism (CDM) where the captured biogas was valued as certified emission reduction (CER) units to earn carbon credit. From 2005-2010, before the expiry of post-Kyoto Protocol (post-KP), the carbon revenue in the form of CER units earned by the industry amounted to 1.24 million tonnes CO_2eq (MGTC, 2013), although currently the CDM has slowed down significantly due to the introduction of a new scheme which is political in nature and still lacks sufficient detail on how such a mechanism will operate. This poses uncertainty to the CDM's fate post-KP and in the future.

BIOGAS CAPTURE AND UTILISATION

POME is cooled while the residual oil in it is removed, and POME in its natural state containing a variety of microorganisms is then placed in a closed digester tank or a covered lagoon to produce biogas *via* AD. Biogas can be captured for different energy applications, *e.g.* for producing electricity for on-grid (connected to the national grid) and off-grid (to power downstream activities) use, for combined heat and power (CHP) to obtain steam and heat, for co-firing in the biomass boiler and diesel generator set to reduce the utilisation of the palm kernel shell (as a boiler fuel) and diesel, *etc*.

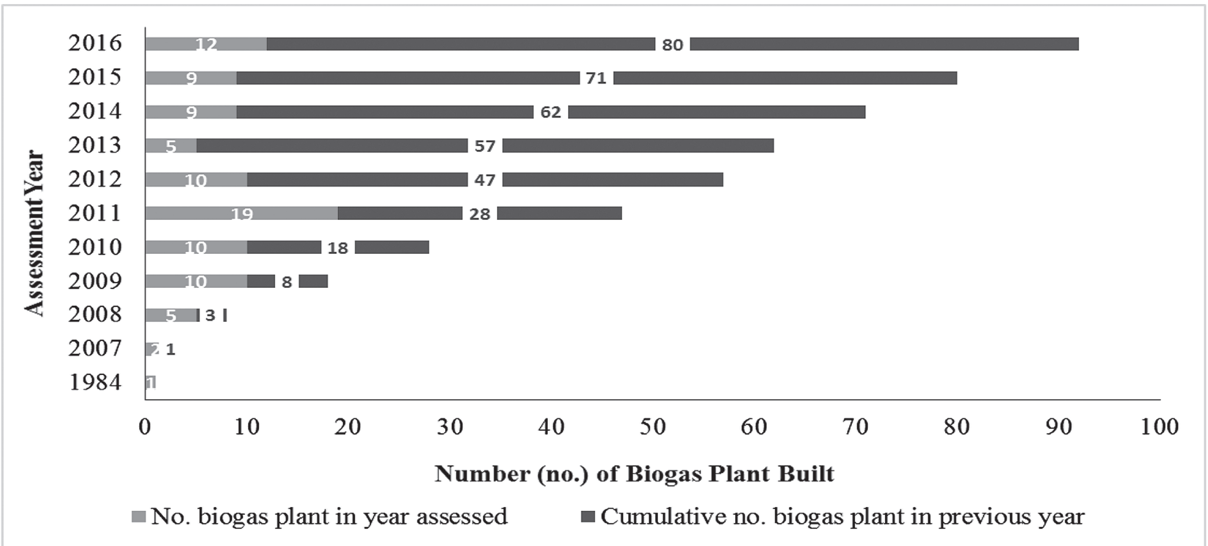
Capturing biogas from POME for various applications has been initiated under the Palm Oil National Key Economic Area (NKEA) of the Economic Transformation Programme (ETP) since 2010 (ETP, 2010). This national implementation program focusing on building biogas trapping facilities at all palm oil mills across the country – Entry Point Project (EPP) 5 – is shouldered by the Malaysian Palm Oil Board (MPOB) as the implementing agency, and its progress is regularly monitored by the MPOB NKEA Biogas Working Group (MPOB WG) which reports to the NKEA Palm Oil and Rubber Steering Committee.

The NKEA EPP5 was initiated as it has both economic and environmental benefits. Its aim is to have all the palm oil mills (453 in 2016) equipped with biogas capture or methane avoidance facilities by 2020 (ETP, 2010). As of December 2016, the palm oil industry has demonstrated a good public-private partnership and recorded rather strong progress in setting up biogas plants, supported by several financial schemes and policies. A cumulative total of 92 biogas plants have been built in the country, while nine are under various stages of construction and another 145 under various stages of planning (*Figure 1*). Sabah tops the list, followed by Johor, Pahang, Perak and Sarawak. There were only a few palm oil mills equipped with biogas trapping facilities during the initial stage before NKEA was launched in 2010. Fortunately, the number of completed biogas plants has grown from year to year, reaching a peak in 2011 (*Figure 1*), due to a spillover effect from the plants previously under construction and from committed CDM-registered projects before post-KP. This national biogas development is the result of a two-pronged implementation strategy supported by (1) the politically-driven NKEA EPP5 (2010), and (2) the Renewable Energy Act (2011). In line with this Act, EPP5 emphasises the use of an inexpensive locally produced waste resource, *i.e.* POME, for electricity generation. The Act – after a 3-year period of monitoring – has revised the Feed-in Tariff (FiT) in 2014 to encourage more uptake; the basic FiT has been raised to RM 0.40 per kW h from its initial RM 0.32 per kW h, and with bonuses it goes up to RM 0.47 per kW h. Besides FiT, others such as tax incentives under the Promotion of Investment Act 1986, and the Green Technology Financing Scheme (GTFS) (GreenTech Malaysia, 2010) are also up for grabs for those wanting to go green with renewable energy generation.

Generally, utilisation of the captured biogas from POME varies from one mill to another depending on the intended use. Biogas can be converted into useful renewable energy either for heat, electricity or both (Loh *et al*., 2014; Persson *et al*., 2006). In Malaysia, the biogas is utilised mainly for 1) steam/heat and electricity generation, 2) solely for steam generation, 3) electricity production, and 4) powering downstream business activities. *Figure 2* shows the various feasible utilisation possibilities of the captured biogas for the completed plants from 1984 to 2016. Of the 92 plants, a total of 12 (14%) co-fire the biogas in the palm oil mill biomass boilers, 24 (28%) generate renewable electricity from the captured biogas, 54 (56%) do not utilize but flare the biogas, while two (2%) use the biogas for thermal energy production (to power the boilers and chillers of the palm oil refinery) (Loh *et al*., 2017). Generally, about half of the biogas captured is for energy production whereas the other half of the plants opts to flare the gas.

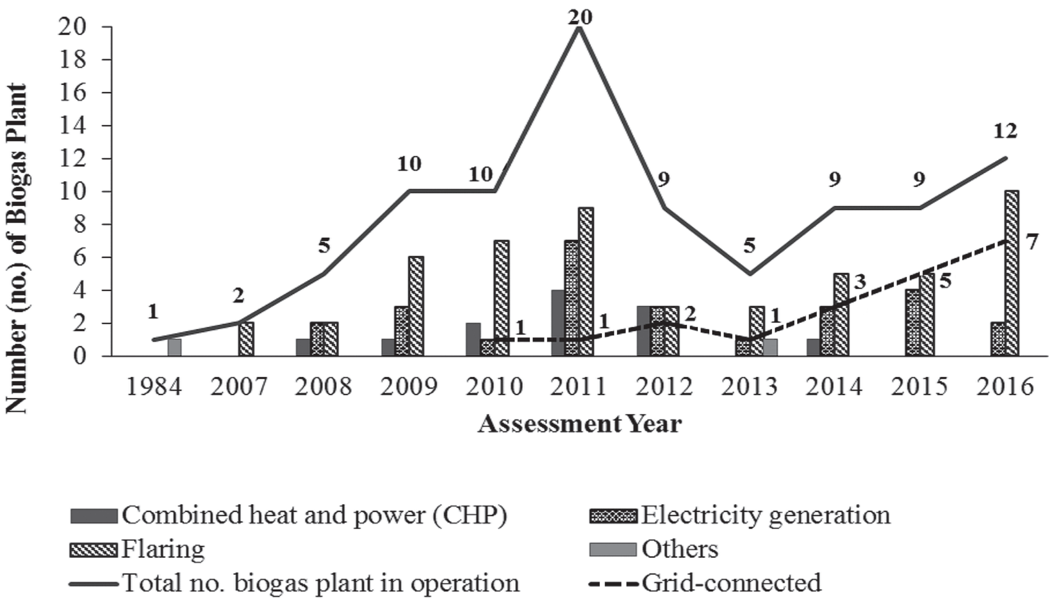
The biogas utilisation trend (2007-2016) (*Figure 2*) shows that the majority of millers owning the biogas plants opted to flare the gas due to 1) surplus energy available and 2) the historical approach during the CDM peak period from 2005-2010. With the expiry of the first CDM commitment period, *i.e.* post-KP 2012, this situation still continued as flaring the biogas was deemed relatively less of a hassle and inexpensive. However, since FiT was revised in 2014, more grid-connected biogas plants have been realised. Currently, 17 are connected to the national grid while three others are hooked onto the local grid supplying electricity for external users surrounding the mill area. In addition, six are under construction and 23 at various stages of planning, making a total of 29 plants in the pipeline to come on board for grid connection in the next two years based on the number of approved Feed-in holders (SEDA, 2016).

In paving the way forward to promote nationwide biogas implementation, it has been mandated that new mills and all existing mills which apply for throughput expansion will need to install full biogas capture or methane avoidance facilities effective 1 January 2014 (MPOB, 2015). Methane avoidance can be conducted practically through co-composting of POME and EFB into compost or organic fertiliser for soil nutrient management in oil palm plantations. To date, there are an estimated 75 composting plants (Nurul Adela *et al*., 2014) – two utilise 90%-100% POME and the rest practise partial utilisation – to be accounted for as part of the solution towards mitigating GHG emissions from the palm oil milling process. Together, these two activities under EPP5 have potentially mitigated 4.379 million tonnes of CO_2eq for biogas (assuming 100% methane combustion) and 1.136 million tonnes for composting – in total an estimated 5.515 million tonnes CO_2eq (Loh *et al*., 2017). Optimistically, there will be more plants coming on stream in the future paving the way towards a cleaner environment with continued government support.



Source: Loh *et al*. (2017).

Figure 1. Status of completed biogas plants in Malaysia (as of December 2016).



Source: Loh *et al*. (2017).

Figure 2. Trend in biogas capture and utilisation (as of December 2016).

One important aspect of mitigating biogas emissions is the reduction of the carbon footprint for palm oil processing. This aspect is very important as the resulting enhanced sustainability will potentially increase the competitiveness and market access of palm products, *e.g*. palm biodiesel in environmentally-sensitive markets such as the European Union (EU) and USA. These countries have set more stringent sustainability standards for the use of renewable energy in combating climate change, as stipulated under the EU Directive on the Promotion of the Use of Energy from Renewable Sources (EU RED) and the USA EPA Renewable Fuel Standard 2 (RSF2 programme).

CURRENT AND EMERGING TECHNOLOGIES

In Malaysia, capturing biogas from POME can be commercially carried out *via* AD using either foreign or locally developed technologies. As of December 2016, 54 palm oil mills employ tank type technologies to digest POME and capture the released biogas, while the other 38 use covered lagoon systems (MPOB WG, 2016) employing readily available microorganisms in POME. To date, the AD-based digester tank type is the most commonly used technology though it is more sophisticated and expensive compared to the simpler covered lagoon type. However, in recent years, covered lagoon technology has been reinvented and improvised, and has showcased some successfully proven high-profile track records in biogas capture; hence, trust has been rebuilt, and reputation and confidence regained by the millers.

At a glance, there are many successful and reliable locally-developed and foreign biogas capture technologies (Loh *et al*., 2014) that have been commercially adopted, *e.g*. from Kim Loong Resources Bhd, CST Engineering Sdn Bhd, Novaviro Technology Sdn Bhd (Tong *et al*., 2016), Cenergi SEA, Alternative Energy Corporation, Konzen Clean Energy Sdn Bhd, Biotec International Asia Sdn Bhd (Kervyn and Conil, 2011), Smart & Green Sdn Bhd (Subbiah and Ahmad, 2010), *etc.* Others are: (1) the methane fermentation system employing special microorganisms jointly developed by MPOB and Biogas Environmental Engineering Sdn Bhd (Lian *et al*., 2011), (2) the hybrid plug-flow system of upflow anaerobic sludge beds (UASB) and expanded granular sludge bed (EGSB) by MPOB and Ronser Bio-Tech Sdn Bhd (Loh *et al*., 2013), and (3) the integrated anaerobic-aerobic bioreactor (IAAB) developed between MPOB and University of Nottingham Malaysia Campus (Yap *et al*., 2017). Comparisons among some of these biogas technologies in terms of working principle, temperature, tank material, *etc*. are presented in *Table 4* (Loh *et al*., 2014; 2017).

Each of these systems is linked to various technological challenges, *i.e.* the robustness of the system to endure fluctuations in POME volume, quality and characteristics of POME, ability of the system to remove solids, the temperature employed and the required hydraulic retention time (HRT) for the system. In *Table 4*, three of the digester systems employ a typical continuously stirred tank reactor (CSTR) mode to ensure homogenous mixing of POME, unlike the other two which have improvised on the mechanism of mixing, hence resulting in a much shorter HRT. BOD/COD removal efficiencies of all these plants were nearly 80% - 90% with a high volume of biogas production – 24-32 m^3 t^{-1} POME – compared to that of the conventional open digester tank system (at 28 m^3 t^{-1} POME) (Ma *et al*., 1994). The covered lagoon systems have similar performance efficiencies despite exhibiting a longer HRT.

To highlight a few: the developed biogas capturing system, namely a high efficiency methane fermentation system (*Figure 3*) employing an upflow solids reactor (USR) concept coupled with specialty microorganisms, was durable. Evaluation/monitoring of the biogas system performance over a year showed that the system is technically mature, and is highly efficient, with a BOD/COD removal rate of 90%-95% and a biogas production rate of 27-30 m^3 t^{-1} POME (Loh *et al*., 2011). To date, more than three biogas plants have been built using this technology. The CSTR developed by Novaviro Technology Sdn Bhd has the longest history of success in Malaysia, with more than 20 biogas plants commercialised to date (Tong *et al*., 2016).

Figure 3. Biogas digester tank at Ladang Sabah Palm Oil Mill.

In addition, zero discharge POME treatment (*Figure 4*) is possible *via* the recovery of usable materials such as oil, biogas, sludge and water from the effluent, and minimising the generation of wastes, and thus need not discharge them into the environment. This system employs an integrated anaerobic-aerobic treatment of POME which produces biogas at 28 m^3 t^{-1} POME with COD removal efficiency of 94% (Loh *et al*., 2013). It has been successfully demonstrated that a properly integrated approach between biogas capture and utilisation system and tertiary polishing treatment of POME could meet both the GHG emissions reduction target and the final discharge of BOD at 20 ppm (Loh *et al*., 2013).

Figure 4. A zero discharge palm oil mill effluent treatment pilot plant at the MPOB's Experimental Palm Oil Mill (POMTEC), Labu.

TABLE 4. EXAMPLES OF BIOGAS TECHNOLOGIES[a] AVAILABLE IN MALAYSIA

Name of technology provider	Working principle/ system	Temperature (⁰C)	Tank material	HRT (day)	Life term (yr)	Final discharge (after digester tank)		Volume of biogas generated (m^3 t^{-1} POME)
						BOD (mg $litre^{-1}$)	COD (mg $litre^{-1}$)	
Novaviro - Keck Seng	Continuous flow stirred tank reactor (CSTR)	35-40	Steel vessel	18	≥20	250-500	80 000-12 000	28
Green & Smart	CSTR (POME-MAS™)	37-40	Mild steel coated with cold tar epoxy paint	14	10	3 500	5 000	24
MPOB-BEE	High efficiency fermentation	31-32	Steel concrete	9	20-25	50-270	1 400-2 500	26-30
Biotec International Asia	Covered lagoon	-	Geo-membrane	27	-	-	-	25[b]
MPOB-Ronser-SJU	AnaEGTM (combination of UASB and EGSB technologies)	35-38	Carbon steel	9	≥20	800-1 000	2 000-2 800	28[c]
Konzen Clean Energy Sdn Bhd	CSTR	37-42	Concrete, mild steel, glass fused	7-10	-	80-90% reduction	80-90% reduction	27-32
Cenergi SEA - Biopower Climate Care	Covered high energy anaerobic pond-CHEAP	38-40	HDPEs	30	15	-	4 500	30

Note: MPOB - Malaysian Palm Oil Board; BEE - Biogas Environmental Engineering; SJU - Shanghai-Jiaotong University; HRT - hydraulic retention time; COD - chemical oxygen demand; BOD - biological oxygen demand; HDPE - high density polyethylene; POME - palm oil mill effluent and FFB - fresh fruit bunches.

[a] The performance of the biogas plants stipulated is based on project references given by the companies. The performance varies from one plant to another. The accuracy and veracity of the information in this table need to be verified independently with the respective technology providers.
[b] in m^3 t^{-1} FFB.
[c] based on 90% COD removal rate, 0.34 m^3 biogas kg^{-1} COD.

Source: Loh *et al*. (2017).

In diversifying biogas utilisation, the world's first commercial POME-based compressed natural gas (BioCNG) plant employing one of the off-site utilisation approaches has been realised (*Figure 5*) at Sg Tengi Palm Oil Mill, Kuala Kubu Bahru, Selangor - a collaboration between MPOB, Felda Palm Industries Sdn Bhd and Sime Darby Offshore Engineering Sdn Bhd. The plant was launched in October 2015. Bottling of biogas to produce pure CH_4 that can be used as a supplementary fuel in industrial processes, household application or as a transport fuel is the way forward in spearheading biogas development in Malaysia.

Figure 5. The first commercial bio-compressed natural gas (BioCNG) plant in Malaysia.

CONCLUSION

Malaysia is blessed with an abundance of renewable resources such as POME which should be treated in a sustainable manner, not just to harness the released biogas as a fuel but also to discharge the final effluent in compliance with BOD of 20 ppm. Biogas capture and utilisation hold much potential and can be made more economically feasible with current governance under FiT to be embraced by an adequately designed supporting framework in the long run. In the future, a more beneficial approach, *i.e.* an integrated biorefinery featuring zero discharge or an 'all-in-one refinery' in a palm oil mill complex, should be pursued taking into account the recovery of all the valuable by-products *via* co-production.

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REFERENCES

BASIRON, Y and CHAN, K W (2004). The oil palm and its sustainability. *J. Oil Palm Res. Vol. 16*: 1-10.

CHAN, K W; WATSON, I and LIM, K C (1981). Use of oil palm waste material for increased production. *The Planter, 57(658)*: 14-37.

DOE (2009). Environmental Requirements - A Guide for Investors. 10th ed. p. 26-56.

ETP (2010). A roadmap for Malaysia-executive summary. Jabatan Perdana Menteri: Pemandu. p. 303-338.

EU RED. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. http://eur-lex.europa.eu/legal-contnet/EN/ALL/?uri=CELEX%3A32009L0028, accessed in July 2015.

GREENTECH MALAYSIA (2010). Malaysian Green Technology Corporation, Green Technology Financing Scheme. https://www.gtfs.my, accessed in July 2015.

KERVYN, B and CONIL, P (2011). Biogas capture using cover lagoon system - Biotec's experience in palm oil mills. Paper presented at the National Seminar on Biogas and Palm Oil Mill Effluent Treatment (Biogas-POMET), Kota Kinabalu, Sabah, 6-7 June 2011.

KONG, S H; LOH, S K; BACHMANN, R T; RAHIM, S A and SALIMON, J (2014). Biochar from oil palm biomass: a review of its potential and challenges. *Renewable and Sustainable Energy Reviews*, *39*: 729-739.

LIAN, L D; LOH, S K; MOHAMAD AZRI, S and CHOO, Y M (2011). Biogas capture and utilization - BEE experience at Tee Teh Palm Oil Mill. Paper presented at the National Seminar on Biogas and Palm Oil Mill Effluent Treatment (Biogas-POMET), Kota Kinabalu, Sabah, 6-7 June 2011.

LIEW, W L; KASSIM, M A; MUDA, K; LOH, S K and AFFAM, A C (2015). Conventional methods and emerging wastewater polishing technologies for palm oil mill effluent treatment: a review. *Journal of Environmental Management*, *149*: 222-235.

LOH, S K (2017). The potential of the Malaysian oil palm biomass as a renewable energy source. *Energy Convers Manage., 141*: 285-298.

LOH, S K and CHOO, Y M (2013). Prospect, challenges and opportunities on biofuels in Malaysia. *Advances in Biofuels* (Pogaku, R and Sarbatly, R eds.). Springer, New York. p. 3-14.

LOH, S K; LIAN, L D; SUKIRAN, M A and CHOO, Y M (2011). A biogas trapping facility for handling palm oil mill effluent (POME). *MPOB Information Series, 564, MPOB TT No. 491*.

LOH, S K; LAI, M E; MUZZAMMIL, N; LIM, W S; CHOO, Y M and ZHANG, Z (2013). Zero discharge treatment technology of palm oil mill effluent. *J. Oil Palm Res. Vol. 25(3)*: 273-281.

LOH, S K; NASRIN, A B; NURUL ADELA, B; MOHAMAD AZRI, S; MUZZAMMIL, N and DARYL JAY, T (2014). Biogas capture and utilization from palm oil mill effluent. MPOB, Bangi, Selangor. p. 1-38.

LOH, S K; NASRIN, A B; MOHAMAD AZRI, S; NURUL ADELA, B; MUZZAMMIL, N; DARYL JAY, T; STASHA ELEANOR, R A; LIM, W S; CHOO, Y M and KALTSCHMITT, M (2017). First report on Malaysia's experiences and development in biogas capture and utilization from palm oil mill effluent under the Economic Transformation Programme: Current and future perspectives. *Renewable and Sustainable Energy Reviews, 74*: 1257-1274.

MA, A N (1999). Treatment of palm oil mill effluent. *Oil Palm and the Environment* (Singh, G, Lim, K H, Teo, L and Lee, K D eds.). Malaysian Oil Palm Growers' Council, Kuala Lumpur, Malaysia. p. 113-123.

MA, A N; CHOO, Y M and YUSOF, B (1994). Renewable energy from the palm oil industry. *J. Oil Palm Res. Vol. 6(2):* 138-146.

MGTC (2013). CDM statistic-energy project – April 2013, quarter 2. http://www.greentechmalaysia.my, accessed in May 2015.

MPOB (2015). E-licensing - License application manual. http://e-licence.mpob.gov.my/infos/Panduan.htm, accessed in May 2015.

MPOB (2016a). Industry Development Unit, Economics and Industry Development Division. http://bepi.mpob.gov.my/index.php/en/our-unit/industry-development-unit.html, accessed in March 2017.

MPOB NKEA Biogas Working Group (WG) (2016). NKEA Biogas Working Group Report - Monthly Update. Engineering and Processing Division, MPOB, Bangi, Selangor.

MPOB (2016b). Malaysia Oil Palm Statistics 2016. 36th ed. MPOB, Bangi, Selangor.

NURUL ADELA, B; LOH, S K; NASRIN, A B; MOHAMAD AZRI, S; MUZZAMMIL, N and DARYL JAY, T (2014). Composting of oil palm biomass-current status in Malaysia. Poster presented at the National Seminar on Palm Oil Milling, Refining, Environment and Quality (POMREQ), Kuching, Sarawak, 3-4 October 2014.

PERSSON, M; JONSSON, O and WELLINGER, A (2006). Biogas upgrading to vehicle fuel standards and grid injection. *IEA Bioenergy Task, 37*: 1-33.

RSF2. USA EPA Renewable Fuel Standard (RFS). http://www.epa.gov/, accessed in July 2015; 40 CFR Part 80 Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule. http://www.gpo.gov/fdsys/pkg/FR-2010-03-26/pdf/2010-3851.pdf, accessed in June 2016.

SEDA (2016). Statistics and Monitoring, FiAH Listing. http://seda.gov.my/?omaneg=00010100000001010100010000100000000000000000000&s=1817, accessed in June 2016.

SUBBIAH, R M and AHMAD, A (2010). Experience on closed anaerobic digesters operation for POME biogas harnessing under CDM project. *Proc. of 2010 National Seminar on Palm Oil Milling, Refining, Environment and Quality*. p. 275-283.

TONG, S L; CHUA, T N and CHUA, N S (2016). Maximising biomass and biogas renewable energy utilization in Keck Seng's integrated palm oil mill and downstream industry complex. *Palm Oil Engineering Bulletin, 120*: 17-21.

VIJAYA, S; MA, A N, CHOO, Y M and NIK, M N S (2008). Life cycle inventory of the production of crude palm oil - a gate to gate case study of 12 palm oil mills. *J. Oil Palm Res. Vol. 20(2)*: 484-494.

VIJAYA, S; MA, A N and CHOO, Y M (2010). Capturing Biogas: a means to reduce greenhouse gas emissions for the production of crude palm oil. *Am J Geosci*, *1(1)*: 1-6.

YAP, C C; LOH, S K; CHONG, M F; CHAN, Y J; SUPRAMANIAM, C V and LIM, L K D (2017). Palm oil potential. *The Chemical Engineer, 910*: 42-45.