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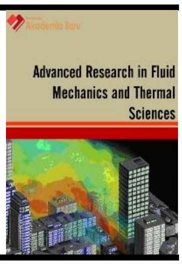

Bio-Methane from Palm Oil Mill Effluent (POME): Transportation Fuel Potential in Malaysia

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ABSTRACT

Palm oil mill effluent (POME) is a waste produced from oil palm processing. It contains high biological oxygen demand (BOD) and chemical oxygen demand (COD). Untreated pome release methane, which has 25 times greenhouse gases (GHG) potential more than carbon dioxide (CO_2). However, trapped POME through anaerobic digestion produced biogas contained 40% to 70% methane. Biogas can be purified into bio-methane for transportation utilization. The potential of biogas production and bio-methane utilization for petrol car were evaluated based on biogas plant registered with clean development mechanism (CDM). It was found that a palm oil mill in Malaysia is capable of producing 1000 – 4200 tons of bio-methane per year and capable of fuelling 1,309, 2,129 and 3,240 cars per year from small, medium and large size palm oil mill. The bio-methane produced can be supplied to near petrol station around palm oil mill for local utilization and reducing GHG released to the atmosphere.

1. Introduction

In recent years, the palm oil industry has grown tremendously and commonly known as vegetable oil found in a commercial product such as soap, chocolate and cooking oil [1]. The global demand for vegetable oil has increased in recent years. Indonesia is the largest supplier of palm oil, followed by Malaysia with a total of 90% globally [2]. Based on data provided by the Malaysian Palm Oil Board (MPOB) in 2016, there are 453 mills in operation and processing about 110,326,200 MT/FFB/Year [3]. Approximately 13% of fresh fruit bunch (FFB) processed from 97,380,600 MT/FFB/Year in 2010. Increasing in the production palm oil had caused abundant of wastewater generated known as effluent.

Palm oil mill effluent (POME) is generated from palm oil mill for processing oil palm, which comprises 95% of water and 5% solids. Moreover, POME contains high chemical oxygen (COD) demand, biological oxygen demand (BOD) and acidity [4]. The presence of bacteria in POME caused

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the organic matter to decomposed and degrading. The degrading process of POME consists of four stages which are hydrolysis and acidogenasis, fermentation, acetogenesis and methanogenesis which lead to the production of biogas [5]. Typically biogas contains 40% to 70% methane (CH_4), and the balance consists of other gases [6].

Anaerobic digestion is widely adopted to treat POME and trapping biogas. It is estimated from 1 ton of FFB oil palm could produce 0.7 POME and 28 m^3 biogas per ton POME [7]. At many palm oil mills, this process already implemented to meet the quality standard for industrial effluent. Methane content in biogas has 25 times GHG potential compared to carbon dioxide (CO_2) if its release into the environment [8]. Clean development mechanism offer certified emission reduction (CER) credit under Kyoto Protocol by utilization of biogas as renewable energy [9]. Other than helping to reduce carbon emission, developing country like Malaysia could attract foreign investments to sustain renewable energy projects through the CDM. Moreover, palm oil mills could earn carbon credits as revenue by utilization of methane gas as renewable energy from anaerobic digestion of palm oil mill effluent.

Some of the local provider that develops biogas capturing technology in Malaysia to commercially capturing biogas are Novaviro – Keck Seng, Green and Smart, MPOB – Biogas Environment Engineering (BEE), Biotec International Asia, MPOB – Ronser – Shanghai Jiaotong University (SJU), Konzen Clean Energy Sdn. Bhd., and Cenergi SEA – Biopower Climate Care [10]. Most of the palm oil mill that captured biogas in Malaysia employs tank-type technologies and covered lagoon systems. The biogas captured is mostly used for boiler, gas engine and the excess was flared. Generated electricity from gas engine is used for own mill usage and some feed into the grid [10].

Renewable energy such as biogas has a high potential for a variety of applications including electricity generation, heating and as fuel for transportation [11]. Further purification of biogas into bio-methane would be more suitable for vehicle fuel. Also, bio-methane fuel has similar engine performance and exhaust emission [6]. Bio-methane has great potential for becoming one of the most sustainable, economical, and environmentally friendly vehicle fuels in the near future. Also, it produces less amount of dangerous and hazardous chemicals such as CO_2, sulphur, lead, and other heavy hydrocarbons into the atmosphere [12]. The potential of bio-methane as an alternative fuel has become one of the most promising transportation fuel for the future. Since Malaysia is the second-largest palm oil producer, it is possible for the country itself to use biogas produced from POME and upgraded to bio-methane for transportation fuel. Despite high production of biogas yet the research on its potential and application for transportation fuel is still lacking. Further study of this bio-methane potential could help local palm oil mills identify the potential of biogas for bio-methane production and transportation utilization. Thus, this study intended to evaluate the potential of bio-methane production from POME and its utilization for a petrol car in Malaysia.

2. Methodology

2.1 Bio-methane Gas Production

The data required for analyzing the potential of bio-methane potential from POME were extracted from palm oil mill participating in clean development mechanism (CDM) under the Kyoto protocol. From the documentation, the production of the total fresh fruit bunch (FFB) per year was used for calculation of POME and biogas production using an estimation method. It is estimated 1 ton of FBB could produce 0.7 POME and the formula is expressed in Eq. (1)-(2) [7].

$$POME_{volume} = FFB_{production} \times 0.7 \tag{1}$$

where $POME_{volume}$ is the volume of wastewater (POME) treated per year [m^3], $FFB_{production}$ is the production of FFB per year [tons], and 0.7 is the default value for estimating POME from FFB [7].

$$Biogas_{production} = POME_{production} \times 28 \tag{2}$$

where $Biogas_{production}$ is the volume of biogas produced from POME [m^3], $POME_{production}$ is the production of POME per year [tons], and 28 is the amount of biogas produced per tons POME [m^3] [7].

According to Shah *et al.,* biogas consists of 40-70% CH_4 on average [6]. Hence, an average of 0.55 is used to calculate the volume of bio-methane production from the biogas produced. The equation is shown in Eq. (3). To convert CH_4 production from m^3 to kg, the calculation is multiplied with a CH_4 density of 0.656 kg/m^3 at normal pressure and temperature (NTP).

$$CH_{4_{production}} = Biogas_{production} \times 0.55 \times \rho_{CH4} \tag{3}$$

where $CH_{4production}$ is the volume of wastewater (POME) treated per year [kg], $Biogas_{production}$ is the production of Biogas per year [m^3], 0.55 is the average fraction of CH_4 contents (range 40-70% CH_4) in biogas and ρ_{CH4} is the density of CH_4 [kg/m^3].

2.2 Potential of Bio-methane Fuel for Vehicle

The potential of bio-methane as a vehicle fuel was then calculated to estimate the distance of the vehicle travel using bio-methane recovered from POME. The evaluation of the bio-methane fuel is based on the fuel consumption of the selected vehicle commonly found in Malaysia. However, the specification of the vehicle is for petrol. A multiplying factor 0.15 from a comparative engine performance of CNG and gasoline from literature review was used to estimate the fuel consumption of bio-methane in vehicles [13]. The data obtained is in liter per 100 kilometer [l/100km] and then converted into kilometer per liter [km/l] and kilometer per kilogram fuel [km/kg]. Multiplying the [km/kg] with the total production of bio-methane giving total distance for vehicles to travel an average 20,000km per year. The equation used is shown in Eq. (4)-(5).

$$Fuel\ cons._{km/kg} = \frac{100}{Fuel\ cons._{l/100km}} \times \rho_{fuel} \tag{4}$$

where Fuel cons. $_{km/kg}$ is the fuel consumption per fuel mass [km/kg], Fuel cons. $_{l/100km}$ is the vehicle fuel consumption for respected fuel [l/100km] and *fuel* is the fuel density [kg/l].

$$Vehicle._{average} = Fuel\ cons._{km/kg} \times CH_{4_{production}} \tag{5}$$

where $Vehicle._{average}$ is the total of vehicle running on bio-methane per year [car/year], Fuel cons. $_{km/kg}$ is the fuel consumption per fuel mass [km/kg], and $CH_{4production}$ is the total estimated of bio-methane production per year [kg].

3. Results and Discussion

3.1 Bio-methane Production from POME

As of June 2019, there are 53 biogas recovery projects from the oil palm industry in Malaysia that registered with CDM program. However, on 50 mills were studied while 3 mills were excluded in this work due to incomplete data. The palm oil mill selected were divided into three categories which are small, medium and large size in term of FFB production, as shown in Table 1, Table 2 and Table 3 respectively. The bio-methane productions from biogas recovery were calculated using the formula given in section 2.1. Out of this project, the estimated FFB ranged from 140,000 to 600,000 tons per year. While the POME produced is ranged from 90,000 to 420,000 m3. Assuming the bio-methane contents in the biogas production is 55% the generated bio-methane is ranged from 1000 to 4200 tons per year.

Table 1
Bio-methane production from POME in Malaysia palm oil mills (small size)

No.	Biogas plant	FFB/Year (tons/yr)	Volume of POME treated (m^3)	Biogas production (m^3)	Volume of bio-methane 55% (m^3)	Bio-methane production (tons)
1	Kilang Kelapa Sawit Bukit Bujang, Segamat, Johor, Malaysia [14]	141,134	98,794	2,766,226	1,521,425	998
2	Carotino Palm Oil Mill, Maran, Pahang, Malaysia [15]	144,000	100,800	2,822,400	1,552,320	1,018
3	Kim Loong Sabah Mills Sdn Bhd, Sabah, Malaysia [16]	150,000	105,000	2,940,000	1,617,000	1,061
4	Keningau Palm Oil Mill Sdn Bhd, Keningau, Sabah, Malaysia [17]	160,444	112,311	3,144,702	1,729,586	1,135
5	Felda Palm Industries Sdn Bhd, Terengganu, Malaysia [18]	174,120	121,884	3,412,752	1,877,014	1,231
6	United Plantations Berhad, Jendarata Palm Oil Mill, Malaysia [19]	180,000	126,000	3,528,000	1,940,400	1,273
7	Syarikat Kretam Mill Sdn. Bhd, Sabah, Malaysia [20]	185,714	130,000	3,640,000	2,002,000	1,313
8	Anson Oil Industries Sdn. Bhd, Teluk Intan, Perak, Malaysia [21]	192,000	134,400	3,763,200	2,069,760	1,358
9	Kilang Sawit Jengka 8 and Kilang Kelapa Sawit Serting, Pahang, Malaysia [22]	198,180	138,726	3,884,328	2,136,380	1,401
10	Felda Palm Industries Sdn. Bhd. Kuantan, Pahang, Malaysia [23]	198,400	138,880	3,888,640	2,138,752	1,403
11	Felda Palm Industries Sdn Bhd, Perak, Malaysia [24]	200,000	140,000	3,920,000	2,156,000	1,414
12	Maokil Palm Mill, Johor, Malaysia [25]	202,500	141,750	3,969,000	2,182,950	1,432
13	Kilang Kelapa Sawit Arah Kawasan Sdn Bhd, Kedah, Malaysia [26]	206,524	144,567	4,047,870	2,226,329	1,460
14	Desa Kim Loong Palm Oil Mill, Kota Tinggi, Johor, Malaysia [27]	210,000	147,000	4,116,000	2,263,800	1,485
15	Kilang Kelapa Sawit Jerantut Sdn Bhd, Pahang, Malaysia [28]	216,560	151,592	4,244,576	2,334,517	1,531
16	TSH Lahad Datu Palm Oil Mill, Sabah, Malaysia [29]	220,000	154,000	4,312,000	2,371,600	1,556

17	KKS PPNJ Kahang, Johor, Malaysia [30]	222,804	155,963	4,366,958	2,401,827	1,576
18	Wujud Wawasan Sdn Bhd, Pahang, Malaysia [31]	236,215	165,351	4,629,814	2,546,398	1,670
19	Bell Palm Industries Sdn Bhd, Batu Batu Pahat, Johor, Malaysia [32]	240,000	168,000	4,704,000	2,587,200	1,697
		Total = 3,678,595	Total = 2,575,017	Total = 72,100,468	Total = 39,655,257	Total = 26,014

Table 2
Bio-methane production from POME in Malaysia palm oil mills (medium size)

No.	Biogas plant	FFB/Year (ton/yr)	Volume of POME treated (m^3)	Biogas production (m^3)	Volume of bio-methane 55% (m^3)	Bio-methane production (tons)
1	Sawira Palm Oil Mill, Pahang and Mukah Kilang Kelapa Sawit, Sarawak, Malaysia [33]	251,682	176,177	4,932,967	2,713,132	1,780
2	UIE Palm Oil Mill, Pantai Remis, Perak, Malasyia [34]	252,000	176,400	4,939,200	2,716,560	1,782
3	Endau Palm Oil Mill Sdn Bhd, Pahang, Malaysia [35]	252,290	176,603	4,944,884	2,719,686	1,784
4	Sapi Palm Oil Mill, Sandakan, Sabah, Malaysia [36]	277,714	194,400	5,443,200	2,993,760	1,964
5	Magenko Renewables Sdn. Bhd. Penang, Malaysia [37]	280,800	196,560	5,503,680	3,027,024	1,986
6	Setia Kawan Kilang Kelapa Sawit (Oil Mill) Sdn Bhd, Kedah, Malaysia [38]	281,735	197,215	5,522,006	3,037,103	1,992
7	FELDA Palm Industries Sdn Bhd, Jempol, Pahang, Malasyia [39]	287,587	201,311	5,636,705	3,100,188	2,034
8	Kilang Sawit Sungai Tengi, Selangor, Malaysia [40]	295,400	206,780	5,789,840	3,184,412	2,089
9	Kilang Kosfarm Sdn Bhd, Pahang, Malaysia [41]	295,837	207,086	5,798,405	3,189,123	2,092
10	R H Plantation Sdn Bhd, Miri, Sarawak [42]	296,078	207,255	5,803,129	3,191,721	2,094
11	Havys Oil Mill Sdn. Bhd, Pahang, Malaysia [43]	300,000	210,000	5,880,000	3,234,000	2,122
12	Foong Lee Sawiminyak Sdn Bhd. Perak, Malaysia [44]	310,052	217,036	6,077,019	3,342,361	2,193
13	Asia Palm Oil Mill, Kinabatangan, Sabah [45]	330,000	231,000	6,468,000	3,557,400	2,334
14	Kilang Minyak Sawit Tg. Tualang, Perak [46]	350,000	245,000	6,860,000	3,773,000	2,475
15	Rompin Palm Oil Mill, Pahang, Malaysia [47]	359,443	251,610	7,045,083	3,874,796	2,542
16	BELL Sri Lingga Sdn Bhd Melaka, Malaysia [48]	360,000	252,000	7,056,000	3,880,800	2,546
17	TSH Sabahan Palm Oil Mill, Sabah, Malaysia [29]	362,366	253,656	7,102,374	3,906,305	2,563
18	Kilang Sawit Jengka 3, Pahang, Malaysia [49]	369,280	258,496	7,237,888	3,980,838	2,611
19	Melewar Properties Sdn Bhd, Sabah, Malaysia [50]	384,000	268,800	7,526,400	4,139,520	2,716

20	QL Palm Oil Mill, Tawau, Sabah, Malaysia [51]	400,000	280,000	7,840,000	4,312,000	2,829
		Total = 6,296,264	Total = 4,407,385	Total = 123,406,780	Total = 67,873,729	Total = 44,525

Table 3
Bio-methane production from POME in Malaysia palm oil mills (large size)

No.	Biogas plant	FFB/Year (ton/yr)	Volume of POME treated (m^3)	Biogas production (m^3)	Volume of bio-methane 55% (m^3)	Bio-methane production (tons)
1	Tian Siang Oil Mill (Perak) Sdn Bhd, Perak, Malaysia [52]	420,000	294,000	8,232,000	4,527,600	2,970
2	Ulu Kanchong Palm Oil Mill, Negeri Sembilan, Malaysia [53]	428,571	300,000	8,400,000	4,620,000	3,031
3	Kim Loong Power Sdn Bhd, Kota Tinggi, Johor, Malaysia [54]	430,000	301,000	8,428,000	4,635,400	3,041
4	Tian Siang Biogas Power (Air Kuning) Sdn. Bhd. Kampar, Perak, Malaysia [55]	449,016	314,311	8,800,714	4,840,392	3,175
5	Sungai Kerang Palm Oil Mill in Sitiawan, Perak, Malaysia [56]	450,000	315,000	8,820,000	4,851,000	3,182
6	KDC Mill 1 & Mill 2, Tawau, Sabah, Malaysia [57]	456,000	319,200	8,937,600	4,915,680	3,225
7	Kilang Kelapa Sawit Lekir Sdn. Bhd. Sitiawan, Perak, Malaysia [58]	471,429	330,000	9,240,000	5,082,000	3,334
8	TSH Kunak Oil Palm Mill, Tawau, Sabah, Malaysia [59]	499,500	349,650	9,790,200	5,384,610	3,532
9	Syarikat Cahaya Muda Perak (Oil Mill) Sdn. Bhd. Tapah, Perak, Malaysia [60]	525,000	367,500	10,290,000	5,659,500	3,713
10	Prolific Yield Palm Oil Mill, Sandakan, Sabah, Malaysia [61]	540,000	378,000	10,584,000	5,821,200	3,819
11	Sungei Kahang Palm Oil Sdn. Bhd, Johor, Malaysia [62]	600,000	420,000	11,760,000	6,468,000	4,243
		Total = 5,269,516	Total = 3,688,661	Total = 103,282,514	Total = 56,805,382	Total = 37,264

Depending on the palm oil mill production rate per hour, the volume of POME produced is directly proportional with 0.7 factors to the amount of FFB processed. However, the production of biogas depends on the type of digester used. Currently, the most common used digester is covered pond or closed anaerobic digester tank. It was reported that closed anaerobic digester tanks have better performance compared to the covered pond. The anaerobic pond system has lower efficiency due to lack of operational control and has a long retention time for degradation [63-64]. The actual production of biogas would be different from the calculation if another parameter is included in the estimation.

3.2 Bio-methane Utilization as Petrol Engine Fuel

The potential of bio-methane as petrol engine fuel was accessed. The assessment focus on the total number of petrol car would be fueled with bio-methane for an assumption of 20,000 kilometres per year. In Table 4 shows petrol vehicle commonly found in Malaysia with engine size ranged from 1000cc to 2500cc. The petrol fuel consumption for each vehicle was gathered to estimated bio-methane fuel consumption based on 0.15 factor obtained from the comparison between petrol engine fuelled by petrol and compressed natural gas (CNG) in the literature [65]. The fuel consumption for CNG is relatively higher because of the lower flame speed of CNG fuel. Hence, the same assumption is used for the bio-methane fuel for the estimation. Naturally, larger engine size required more fuel for combustion. The same amount of fuel resulting less distance travel for large engine and this condition also applied for other fuel such as bio-methane. The average bio-methane fuel consumption was estimated to be 19.13 km/kg where is nearly represents the mid-size engine capacity of the vehicles available in Malaysia.

Table 5 shows the average number of petrol car fuelled with bio-methane based on average fuel consumption from Table 4. From Table 5, 50 palm oil mills were divided into three category which is small (100,000 – 250,000 tons/year), medium (250,000 – 400,000 tons/year) and large (400,000 – 600,000 tons/year). It was estimated 26,014, 44,525, 37,264 tons/year of bio-methane were produced from small, medium and large size mill with a total of 107,803 tons/year. Other, than that, an average of 1,309 cars can be fuelled with bio-methane for each small palm oil mill. While 2,129 and 3,240 cars per year for each medium and large palm oil mill respectively. It is estimated that a total of 103,091 cars can be fuelled with bio-methane per year from palm oil mill participated in CDM project.

Table 4
Fuel Consumption for common vehicle found in Malaysia ranged 1000 cc to 2500 cc [66]

Vehicles	Engine Size (cc)	Petrol Fuel Consumption (L/100km)	Bio-methane Fuel Consumption (L/100km)	Petrol Fuel Consumption (km/kg)	Bio-methane Fuel Consumption (km/kg)
Perodua Axia (AT) 2018	998	4.40	5.06	30.10	26.18
Perodua Bezza (AT) 2018	1,329	4.80	5.52	27.59	23.99
Toyota Vios (AT) 2019	1,496	5.80	6.67	22.84	19.86
Honda HRV (AT) 2019	1,799	6.60	7.59	20.07	17.45
Toyota Harrier (AT) 2018	1,998	7.60	8.74	17.43	15.15
Toyota Vellfire (AT) 2018	2,494	9.50	10.93	13.94	12.12
					Average = 19.13

Table 5
Number of car fuel with bio-methane produced from POME per year

Palm oil mill size	Mill quantity	FFB production (tons/yr)	Bio-methane production (tons/yr)	Ave. bio-methane per mill (tons/yr)	Ave. car fuelled by bio-methane at 20,000km per mill (car/yr)	Total car fuelled by bio-methane
Small	19	100,000-250,000	26,014	1,369	1,309	24,871
Medium	20	250,000-400,000	44,525	2,226	2,129	42,580
Large	11	400,000-600,000	37,264	3,388	3,240	35,640
	Total = 50		Total = 107,803			Total = 103,091

4. Conclusions

The potential of bio-methane production and utilization for petrol car from POME were estimated. It was found that palm oil mills in Malaysia are capable of producing 26,014, 44,525 and 37,264 tons of bio-methane per year from small, medium and large mill respectively, with a total of 107,803 tons per year. The potential of bio-methane utilization for petrol car also being estimated and the result shows 1,309, 2,129 and 3,240 cars can be fuelled with bio-methane per year from each small, medium and large mill respectively. Utilization of bio-methane produced from POME may help reduce CH_4 gas released into the atmosphere and decrease global warming potential. Furthermore, bio-methane provides renewable and sustainable fuel solution to substitute fossil CNG for transportation utilization. The result shows an estimated total of 103,091 cars in Malaysia can be fuelled with bio-methane throughout a year when all the palm oil mills from CDM were taken into account. Further estimation which includes other usages of bio-methane in palm oil mill would be very beneficial to estimate the true potential of bio-methane for transportation fuel.

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References
[1] Chin, May Ji, Phaik Eong Poh, Beng Ti Tey, Eng Seng Chan, and Kit Ling Chin. "Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia's perspective." *Renewable and Sustainable Energy Reviews* 26 (2013): 717-726.
[2] Raman, Sharvini Siva, Zainura Zainon Noor, S. S. Syed Narolhisa, Chun Shiong Chong, and Lindsay C. Stringer. "Energy Generation from Palm Oil Mill Effluent (POME): The Environmental Impact Perspective." *Chemical Engineering Transactions* 72 (2019): 25-30.
[3] Mampu, "Malaysia: palm oil mills and refineries," 2017. [Online]. Available: http://www.data.gov.my/data/ms_MY/dataset/malaysia-palm-oil-mills-and-refineries-2016/resource/fbc9fb5d-35e7-4280-880c-e24cbda6a712. [Accessed: 04-July-2019].
[4] Mohtar, Aminullah, Wai Shin Ho, Ahmad Muzammil Idris, Haslenda Hashim, Jeng Shiun Lim, Peng Yen Liew, Gabriel Ling Hoh Teck, and Chin Siong Ho. "Palm Oil Mill Effluent (POME) Biogas Techno-Economic Analysis for Utilisation as Bio Compressed Natural Gas." *Chemical Engineering Transactions* 63 (2018): 265-270.
[5] Poh, P. E., and M. F. Chong. "Development of anaerobic digestion methods for palm oil mill effluent (POME) treatment." *Bioresource technology* 100, no. 1 (2009): 1-9.
[6] Shah, M. S., P. K. Halder, A. S. M. Shamsuzzaman, M. S. Hossain, S. K. Pal, and E. Sarker. "Perspectives of biogas conversion into Bio-CNG for automobile fuel in Bangladesh." *Journal of Renewable Energy* 2017 (2017): 1–14.
[7] Aziz, N. I. H. A., and Marlia M. Hanafiah. "The potential of palm oil mill effluent (POME) as a renewable energy source." *Journal of Green Energy* 1, no. 2 (2017): 323-346.
[8] Reijnders, Lucas, and M. A. J. Huijbregts. "Palm oil and the emission of carbon-based greenhouse gases." *Journal of cleaner production* 16, no. 4 (2008): 477-482.
[9] Loh, S. K., A. Nasrin, S. Mohamad Azri, B. Nurul Adela, and N. Muzzammil. "Biogas Capture–A Means of Reducing Greenhouse Gas Emissions from Palm Oil Mill Effluent." *Oil Palm Bulletin* 75 (2017): 27-36.
[10] Loh, S. K., A. B. Nasrin, S. Mohamad Azri, B. Nurul Adela, N. Muzzammil, T. Daryl Jay, RA Stasha Eleanor, W. S. Lim, Y. M. Choo, and M. Kaltschmitt. "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 (2017): 1257-1274.
[11] Mohtar, A., W. S. Ho, H. Hashim, J. Sh Lim, Z. A. Muis, and P. Y. Liew. "Palm Oil Mill Effluent (POME) Biogas Off-site Utilization Malaysia Specification and Legislation." *Chemical Engineering Transactions* 56 (2017): 637-642.
[12] Khan, Imran Ullah, Mohd Hafiz Dzarfan Othman, Haslenda Hashim, Takeshi Matsuura, A. F. Ismail, M. Rezaei-DashtArzhandi, and I. Wan Azelee. "Biogas as a renewable energy fuel–A review of biogas upgrading, utilisation and storage." *Energy Conversion and Management* 150 (2017): 277-294.

[13] Jahirul, Mohammad I., Haji Hassan Masjuki, Rahman Saidur, M. A. Kalam, M. H. Jayed, and M. A. Wazed. "Comparative engine performance and emission analysis of CNG and gasoline in a retrofitted car engine." *Applied Thermal Engineering* 30, no. 14-15 (2010): 2219-2226.
[14] CDM, "Project 2641: AMA08-W-22, Methane Recovery in Wastewater Treatment, Johor, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244392852.03/view. [Accessed: 11-Jun-2019].
[15] CDM, "project 6762: Methane Capture and Utilization Project at Carotino Palm Oil Mill, Malaysia," 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1343013701.33/view. [Accessed: 11-Jun-2019].
[16] CDM, "Project 7473: Methane capture for onsite utilization at Kim Loong Sabah Mills Sdn. Bhd.," 2012. [Online]. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1350553642.41/view. [Accessed: 11-Jun-2019].
[17] CDM, "Project 2656: AMA08-W-08, Methane Recovery in Wastewater Treatment, Sabah, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1350553642.41/view. [Accessed: 11-Jun-2019].
[18] CDM, "Project 2651: Felda Chalok and Jerangau Barat Biogas Project," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SGS-UKL1244459250.37/view. [Accessed: 11-Jun-2019].
[19] CDM, "Project 1153: Methane recovery and utilisation project at United Plantations Berhad, Jendarata Palm Oil Mill, Malaysia," 2007. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1181122330.1/view. [Accessed: 12-Jun-2019].
[20] CDM, "Project 6487: Kretam Wastewater Biogas Recovery and Utilisation Project, in Sandakan, Sabah Malaysia," 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1340630088.28/view. [Accessed: 11-Jun-2019].
[21] CDM, "Project 2949: Biogas Project at Anson Oil Mill," 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1251857937.76/view. [Accessed: 11-Jun-2019].
[22] CDM, "Project 1756: MY08-WWP-34, Methane Recovery in Wastewater Treatment, Pahang and Negeri Sembilan, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1206699817.97/view. [Accessed: 12-Jun-2019].
[23] CDM, "Project 2603: Felda Pancing and Pasoh Biogas Project," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SGS-UKL1243418372.88/view. [Accessed: 11-Jun-2019].
[24] CDM, "Project 2542: FELDA Besout POME Biogas Project," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1240570936.59/view. [Accessed: 11-Jun-2019].
[25] CDM, "Project 2653: Felda Maokil and Kemahang POME Biogas Project," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SGS-UKL1244474068.28/view. [Accessed: 11-Jun-2019].
[26] CDM, "Project 2665: Methane Recovery in Wastewater Treatment, Project AMA07-W-07, Kedah, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244556873.7/view. [Accessed: 11-Jun-2019].
[27] CDM, "Project 1737: Methane Recovery for Onsite Utilisation Project at Desa Kim Loong Palm Oil Mill, Sook, Keningau, Sabah, Malaysia," 2008. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1205408484.51/view. [Accessed: 11-Jun-2019].
[28] CDM, "Project 2655: Methane Recovery in Wastewater Treatment, Project AMA07-W-05, Pahang, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244500068.49/view. [Accessed: 11-Jun-2019].
[29] CDM, "Project 2330: Methane recovery and utilisation project at TSH Lahad Datu Palm Oil Mill, Sabah, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1227799476.62/view. [Accessed: 11-Jun-2019].
[30] CDM, "Project 2632: AMA08-W-21, Methane Recovery in Wastewater Treatment, Johor, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244214636.83/view. [Accessed: 12-Jun-2019].
[31] CDM, "Project 1738: MY08-WWP-36, Methane Recovery in Wastewater Treatment, Pahang, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1205410957.4/view. [Accessed: 11-Jun-2019].
[32] CDM, "Project 1783: Methane capture from POME for electricity generation in Batu Pahat.," 2008. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SGS-UKL1207602299.44/view. [Accessed: 12-Jun-2019].
[33] CDM, "Project 3636: Methane Recovery and Utilisation Bundled Project GL1 for Mukah Kilang Kelapa Sawit and Sawira Palm Oil Mill.," 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1270973279.95/view. [Accessed: 11-Jun-2019].
[34] CDM, "Project 3622: Biogas Plant at United Plantations Berhad, UIE Palm Oil Mill," 2011. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1270640666.51/view. [Accessed: 11-Jun-2019].
[35] CDM, "Project 2657: MY08-WWP-26, Methane Recovery in Wastewater Treatment, Pahang, Malaysia," 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244503368.32/view. [Accessed: 11-Jun-2019].
[36] CDM, "Project 7587: Sapi Palm Oil Mill Effluent Methane Recovery Project," 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1349324176.23/view. [Accessed: 11-Jun-2019].

[37] CDM, “Project 7785: Magenko Renewables (Penang) Wastewater Methane Avoidance and Energy Generation Project, Malaysia,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1350553642.41/view. [Accessed: 12-Jun-2019].
[38] CDM, “Project 2623: AMA08-W-10, Methane Recovery in Wastewater Treatment, Kedah, Malaysia,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244037446.46/view. [Accessed: 11-Jun-2019].
[39] CDM, “Project 2336: FELDA Serting Hilir Biogas Power Plant Project,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SGS-UKL1227808382.8/view. [Accessed: 11-Jun-2019].
[40] CDM, “Project 9263: FELDA Biogas Plant (Methane Recovery and Utilisation) at Sungai Tengi Palm Oil Mill, Malaysia,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1356601292.39/view. [Accessed: 12-Jun-2019].
[41] CDM, “Project 2642: AMA08-W-24, Methane Recovery in Wastewater Treatment, Pahang, Malaysia,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244395555.72/view. [Accessed: 12-Jun-2019].
[42] CDM, “Project 2635: AMA08-W-23, Methane Recovery in Wastewater Treatment, Sarawak, Malaysia,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1244323078.66/view. [Accessed: 11-Jun-2019].
[43] CDM, “Project 6939: Biopower Climate Care POME Biogas Capture and Utilization Project in Palong, Malaysia,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1344338343.65/view. [Accessed: 11-Jun-2019].
[44] CDM, “Project 1616: Methane Recovery in Wastewater Treatment, Project AMA07-W-01, Perak, Malaysia,” 2016. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1202922119.15/view. [Accessed: 12-Jun-2019].
[45] CDM, “Project 7245: Methane Capture and Utilization Project at Asia Palm Oil Mill, Malaysia,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1347336155.79/view. [Accessed: 11-Jun-2019].
[46] CDM, “Project 9245: Kilang Minyak Sawit Tg. Tualang Mill Wastewater Biogas Recovery and Utilisation Project,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-RHEIN1356578940.83/view. [Accessed: 11-Jun-2019].
[47] CDM, “Project 2602: AMA08-W-25, Methane Recovery in Wastewater Treatment, Pahang, Malaysia,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1243347186.98/view. [Accessed: 12-Jun-2019].
[48] CDM, “Project 5825: Biogas and electricity generation in Kuala Sungai Baru, Malaysia,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1329901987.95/view. [Accessed: 11-Jun-2019].
[49] CDM, “Project 4216: MY08-WWP-30, Methane Recovery in Wastewater Treatment, Pahang, Malaysia,” 2011. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-RHEIN1291830796.68/view. [Accessed: 12-Jun-2019].
[50] CDM, “Project 6488: Methane Capture and Utilization Project at Melewar Palm Oil Mill, Malaysia,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1340630384.1/view. [Accessed: 11-Jun-2019].
[51] CDM, “Project 9122: Palm Oil Mill Effluent Methane Recovery & Utilisation System at QL Palm Oil Mill 1 at Tawau, Sabah,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/RWTUV1356264655.78/view. [Accessed: 11-Jun-2019].
[52] CDM, “Project 6932: Tian Siang Oil Mill (Perak) Biogas Project,” 2012. [Online]. Available: https://cdm.unfccc.int/Projects/DB/RWTUV1344254207.72/view. [Accessed: 11-Jun-2019].
[53] CDM, “Project 3125: Biogas Recovery at Ulu Kanchong Palm Oil Mill,” 2011. [Online]. Available: https://cdm.unfccc.int/Projects/DB/RWTUV1257518413.1/view. [Accessed: 11-Jun-2019].
[54] CDM, “Project 0867: Kim Loong Methane Recovery for Onsite Utilization Project at Kota Tinggi, Johor, Malaysia.,” 2007. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1169205863.92/view. [Accessed: 12-Jun-2019].
[55] CDM, “Project 2560: Tian Siang Oil Mill (Air Kuning) Biogas Project,” 2013. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1241676719.87/view. [Accessed: 12-Jun-2019].
[56] CDM, “Project 2185: Methane Capture and On-site Power Generation Project at Sungai Kerang Palm Oil Mill in Sitiawan, Perak, Malaysia,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1218647963.33/view. [Accessed: 12-Jun-2019].
[57] CDM, “Project 3639: KDC MILL 1 AND MILL 2 BIOGAS PROJECT,” 2010. [Online]. Available: https://cdm.unfccc.int/Projects/DB/SIRIM1270974329.14/view. [Accessed: 12-Jun-2019].
[58] CDM, “Project 1888: KKSL Lekir Biogas Project, Project BCM07_SLK_14,” 2008. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-RHEIN1214554831.51/view. [Accessed: 11-Jun-2019].

[59] CDM, “Project 0916: Methane Recovery and Utilisation Project at TSH Kunak Oil Palm Mill,” 2008. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1170423084.93/view. [Accessed: 11-Jun-2019].

[60] CDM, “Project 2181: Methane Capture and On-site Power Generation Project at Syarikat Cahaya Muda Perak (Oil Mill) Sdn. Bhd. in Tapah, Perak, Malaysia,” 2009. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-SUED1218645135.67/view. [Accessed: 11-Jun-2019].

[61] CDM, “Project 4285: Biogas Project at Prolific Yield Palm Oil Mill,” 2011. [Online]. Available: https://cdm.unfccc.int/Projects/DB/DNV-CUK1293013442.51/view. [Accessed: 12-Jun-2019].

[62] CDM, “Project 3686: Sungei Kahang POME Biogas Recovery for Energy Project in Johor, Malaysia.,” 2010. [Online]. Available: https://cdm.unfccc.int/Projects/DB/TUEV-RHEIN1273459520.7/view. [Accessed: 11-Jun-2019].

[63] Ma, A. N., and Augustine SH Ong. "Pollution control in palm oil mills in Malaysia." *Journal of the American Oil Chemists' Society* 62, no. 2 (1985): 261-266.

[64] Chan, Yi Jing, Mei Fong Chong, and Chung Lim Law. "An integrated anaerobic–aerobic bioreactor (IAAB) for the treatment of palm oil mill effluent (POME): Start-up and steady state performance." *Process Biochemistry* 47, no. 3 (2012): 485-495.

[65] Aljamali, Saad, W. M. F. W. Mahmood, Shahrir Abdullah, and Yusoff Ali. "Comparison of performance and emission of a gasoline engine fuelled by gasoline and CNG under various throttle positions." *Journal of Applied Sciences* 14, no. 4 (2014): 386.

[66] CarBase.my, “Malaysia’s #1 Car Buyer’s Guide,” 2019. [Online]. Available: https://www.carbase.my/. [Accessed: 12-Jun-2019].