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Palm Oil Mill Effluent (POME) Characteristic in High Crop Season and the Applicability of High-Rate Anaerobic Bioreactors for the Treatment of POME

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Palm oil mill effluent (POME) is a wastewater generated from palm oil milling activities which requires effective treatment before discharge into watercourses due to its highly polluting properties. The characterization of wastewater is the essential step in the design of any wastewater treatment plant (WWTP) in the industry as conducting pilot-scale tests to obtain design and operating parameters is time-consuming and expensive. Characterization of POME had been conducted in various studies which only involve parameters that were listed as discharge standards by local environmental authorities and those that were significant to the results of the chosen treatment methods. Other important parameters that were seldom considered in the characterization of POME are as follows: total phosphorus (TP), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), total volatile solids (TVS), volatile suspended solids (VSS), lignin and sulfate concentrations, and toxicity. These parameters are very important in determining the suitable treatment method for industrial-scale WWTP designs besides detecting the operational problems of the selected treatment system due to the characteristics of POME. This would also ensure a proper process design and equipment sizing for POME treatment systems. Therefore a comprehensive POME characteristic study was conducted in the present research with two main objectives: (i) to obtain a complete, up to date, and representative characteristic of POME which is important for treatment method selection, process design, and equipment sizing for industrial-scale WWTP and (ii) to evaluate the suitability of POME to be treated anaerobically on the basis of the characteristic study. POME characteristics sampled from Golconda palm oil mill at high crop season was found to have deviated at approximately ±20−50% from the values recorded during low crop season. An overall characteristic of POME obtained from this study indicated that the biochemical oxygen demand (BOD) concentration in POME was 49000 mg/L; chemical oxygen demand (COD) was 79000 mg/; total volatile solids (TVS) concentration was 42600 mg/L; and COD:N:P ratio of POME was 250:2.9:3.2. The POME characteristic obtained in this study indicated that POME treatment using anaerobic systems was a viable option due to the high biodegradability of the POME and the versatility of high-rate anaerobic bioreactors to cope the variation and fluctuation of POME characteristics. Furthermore, the introduction of the clean development mechanism (CDM) encourages the utilization of high-rate anaerobic bioreactors for POME treatment and methane capture to earn certified emission reduction (CER) credits as a source of revenue.

1. Introduction

Palm oil mill effluent (POME) is a wastewater produced from sterilization, hydrocyclone waste, and separator sludge in the course of crude palm oil production where separator sludge and sterilizer effluent are the two major sources of POME which contribute to the highly polluting characteristics of the wastewater.[1] The characteristics of each separate source are shown in Table 1.[2] Direct discharge of POME causes detrimental effect to the environment due to its highly polluting characteristics, especially in Malaysia, where approximately 53 million tons of POME had been produced in year 2008, based on the fact that 3 tons of POME is being generated from a ton of crude palm oil produced in palm oil mills.[2]

The characterization of wastewater plays a fundamental part in the wastewater treatment process in decisions made about an appropriate and economical wastewater treatment method so that the treated effluent is able to meet the discharge limits set by local environmental authorities.[3] It is of particular importance in the industry to conduct a characteristic study on a wastewater because the characterization would provide the essential information which could enable a proper wastewater treatment plant design. Conducting laboratory- or pilot-scale experiments to acquire suitable design parameters for the wastewater treatment plant is time-consuming, and thus, industrial practice could only depend on the information obtained through the characteristic study of the wastewater. The parameters and the imposed limits on the discharge for treated POME that were made mandatory for monitoring by the Department of Environment (DOE), Malaysia are listed in Table 2.

Table 3 shows the various parameters that were measured in previous POME characteristics studies, and most of the measured parameters were confined to those parameters required by DOE as shown in Table 2. In addition, some of the POME characteristics published in the literature were done on the basis of the requirements of the selected treatment method whereby only parameters that were significant to the result of the study were quantified.[7,9,10]

Anaerobic digestion is the most common method for primary POME treatment. More than 85% of the palm oil mills in Malaysia have adopted the ponding system while the rest opted for open digesting tanks.[12] In recent years, the focus of POME treatment has shifted from conventional methods (i.e., ponding system, open digesting tanks) to the application of high-rate bioreactors also due to their advantage in producing and capturing biogas, a shorter retention time, and smaller space requirements.[11] Alternative methods that were applied on POME

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Table 1. Properties of POME from Sterilization, Hydrocyclone Waste, and Separator Sludge[2]

param[a]	sterilizer effluent	hydrocyclone effluent	separator sludge
biochemical oxygen demand (BOD)	10 000−25 000		17 000−35 000
chemical oxygen demand (COD)	30 000−60 000		40 000−75 000
total solids (TS)	40 000−50 000	5000−15 000	35 000−70 000
suspended solids (SS)	3000−5000	5000−12 000	12 000−18 000
oil and grease (O&G)	2000−3000	1000−5000	5000−15 000
ammoniacal nitrogen (NH_3−N)	20−50		20−50
total nitrogen (TN)	350−600	70−150	500−900
pH	4.5−5.5		3.5−4.5

[a] All parameters are listed in milligrams per liter, except for pH which has no units.

Table 2. Environmental Quality Act 1974 for POME Discharge

param[a]	limit	param[a]	limit
BOD_3	100	NH_3−N	150
COD	[b]	TN	200
TS	[b]	pH	5−9
SS	400	temp (°C)	45
O&G	50		

[a] All parameters are listed in milligrams per liter, except for pH which has no units. [b] No discharge standard after 1984.

treatment were membrane filtration,[13] aerobic systems[14] and evaporation.[15] However, these systems were not implemented in large scale[16] due to operational problems such as scum formation, sludge flotation,[17] or high-energy requirements from the treatment system.

On the other hand, the development of high-rate anaerobic bioreactors enabled better POME treatment efficiency and short hydraulic retention times and has a low energy demand.[7] To date, POME has been treated anaerobically using an upflow anaerobic sludge blanket (UASB),[1] upflow anaerobic sludge-fixed film (UASFF),[7] anaerobic contact digester,[18] expanded granular sludge bed (EGSB),[17] and anaerobic filter and fluidized bed reactor.[1] These high-rate anaerobic bioreactors could reduce at least 90% of COD in POME, except for the fluidized bed where it only managed a 78% COD reduction.[19] Nevertheless, the mentioned high-rate anaerobic bioreactors also faced operating problems (i.e., scum formation, clogging of pipes, etc.) when a high organic loading rate (OLR) was applied to the system. The operational problems which led to the ineffciency of the system indicated alack of knowledge and data on the POME characteristics. Operational problems such as scum formation and sludge flotation were in fact due to the high concentrations of SS and O&G present in POME. Thus, it is important to characterize POME in order to detect potential operational problems due to the characteristics of POME before process and equipment design and also to work on the countermeasures to prevent such operational problems.

In addition, the introduction of the clean development mechanism (CDM) allows developing countries to earn certified emission reduction (CER) credits, which is a source of revenue. These factors have escalated the application of high-rate anaerobic bioreactors for POME treatment. Therefore, a more complete wastewater characteristic study on POME is essential for a successful design of a high-rate anaerobic bioreactor registered under a CDM project which could maximize treatment efficiency as well as biogas production with high methane purity, capitalizing on the CER credits. Hence, the characteristic study of POME in the present research is focused toward the parameters for biological treatment to evaluate the suitability of POME to be treated anaerobically with high-rate anaerobic bioreactors.

Other parameters of POME that were not often quantified in the literature were total phosphorus (TP), total organic carbon (TOC), total Kjehldahl nitrogen (TKN), total volatile solids (TVS), volatile suspended solids (VSS), lignin and sulfate concentrations, and toxicity. In terms of biological treatment, the quantification of TOC, TVS, and VSS is essential for determining the biodegradability of the POME while the amount of TP reflects the availability of nutrients in POME for the growth of microbes. Lignin is a compound which is difficult to degrade biologically and is the cause of the high concentration of dissolved organic matter, the color, and odor of the wastewater.[20] The lignin concentration has to be taken into account in the selection of an optimal treatment method and operating parameters to ensure adequate removal of organic matter. Toxicity in wastewater might lead to the inhibition of biological activities in a biological treatment system.[21] Hence, the measurement of the toxicity of POME is essential for determining the relative degree of toxicity of POME to living organisms. Sulfide produced from anaerobic digestion through the reduction of sulfate ions and sulfate-containing compounds (i.e., protein) is toxic to methanogens in the system.[22] Thus, it is important

Table 3. Measured Parameters of POME from Previous Characteristic Studies

param[a] (mg/L)	Ma and Ong[4]	Ahmad et al.[5]	MPOB[6]	Zinatizadeh et al.[7]	Choorit and Wisarnwan[8]	Wu et al.[9]	Oswal et al.[10]	Zhang et al.[11]
BOD_3	25 000	25 000	25 000	22 700	65 714	N/A	11 000	N/A
COD_{Cr}	N/A	50 000	50 000	44 300	102 696	70 900	246 000	79723
$sCOD_{Cr}$	N/A	N/A	N/A	17140	N/A	N/A	N/A	N/A
TS	N/A	40 500	45 000	N/A	72 058	N/A	N/A	67 200
TVS	N/A	N/A	34 000	N/A	N/A	N/A	N/A	49 300
SS	19 000	18 000	18 000	19 780	46 011	25 800	N/A	N/A
O&G	8000	4000	4000	4850	9341	N/A	N/A	17410
NH_3−N	35	N/A	35	N/A	103	N/A	N/A	N/A
TN	770	750	750	N/A	N/A	N/A	N/A	N/A
TKN	N/A	N/A	N/A	780	1381	N/A	N/A	672
VFA	N/A	N/A	N/A	2510	4202	N/A	N/A	2287
pH[b]	4.5	4.7	4.7	4.05	4.4	4.52	5	4.8
temp (°C)	80−90	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[a] COD_{Cr}, chemical oxygen demand; $sCOD_{Cr}$, soluble chemical oxygen demand; TVS, total volatile solids; TKN, total Kjeldahl nitrogen; VFA, volatile fatty acids; N/A, data not available. [b] No units for pH.

to quantify the concentration of sulfate in POME to estimate the impact of sulfate reduction to the toxicity of an anaerobic system.

To date, not much emphasis has been placed in evaluating these parameters and their effects on the efficiency of the selected method, especially for an anaerobic digestion method apart from the studies conducted by Ho et al.[23] and Hwang et al.,[3] who investigated the distribution of chemical constituents (i.e., solid, protein, and ash content, etc.) of POME and its significance on treatment or utilization. Nevertheless, the parameters that were characterized for POME were not suitable to be utilized for equipment selection and design. Moreover, the data in these literatures were not updated in recent studies and might no longer be a representative value of POME. As such, there is a need to conduct a comprehensive POME characteristic study to provide the most updated value of POME characteristics that can be utilized for biological treatment system designs.

On the basis of Table 2, there were large variations between the POME characteristics obtained by Choorit and Wisarnwan,[8] Wu et al.,[9] Oswal et al.,[10] and Zhang et al.[11] with the rest of the literature values. The season when POME was sampled is a possible reason for the differences in the values. The harvesting of fresh fruit bunches (FFB) of palm oil can be separated into two seasons. The low crop season commences in the month of November until the end of May and June marks the start of a high crop season and ends in the month of November.[24] During high crop season more FFBs were processed, and this would have been a factor which caused the variation. So far, investigation has not been done to study the variation of POME characteristics between low and high crop seasons. It is important to investigate the variation of POME characteristics in order to obtain a characterization of POME which is representative.

Therefore, a comprehensive POME characterization study was conducted in the present research to obtain the most recent, complete, and typical POME characteristic which would serve as a beneficial piece of information to the palm oil milling industry. This study will also demonstrate how the data obtained from the characteristic study was used to evaluate the suitability of the proposed system (anaerobic system in this case) for POME treatment. POME samples from three palm oil mill sites in Selangor, Malaysia were obtained for the characterization study. The differences in the characteristics of POME during low crop season and high crop season were also investigated by using the samples collected from Golconda palm oil mill. Furthermore, the suitability of anaerobic systems for POME treatment and its impact on the implementation of CDM projects were also discussed.

2. Materials and Methods

2.1. Site Locations. Three sampling sites were selected among the palm oil mills in Selangor, Malaysia for on-site sampling and sample collections. The three identified sites were as follows: (1) Golconda Palm Oil Mill, Persiaran Hamzah Alang, off Jalan Kapar, Jalan Kapar, 42200 Klang, Selangor; (2) Kilang Kelapa Sawit Bukit Kerayong, Bukit Kerayong Road, 42200 Kapar, Klang, Selangor; (3) Seri Ulu Langat Palm Oil Mill, Lot 3115, Batu 34, Jalan Banting, Dengkil, 43800, Selangor.

The sampling point for both Golconda and Seri Ulu Langat palm oil mills were situated at the outlet of the oil trap, before the wastewater was discharged into their respective treatment systems. Unlike Golconda and Seri Ulu Langat palm oil mills, the sampling point for Bukit Kerayong palm oil mill was located before the oil trap due to accessibility and safety concerns. Figure 1 indicates the sources of POME from palm oil milling activities as well as the sampling points in the mills, which are denoted as A (Bukit Kerayong palm oil mill) and B (Golconda and Seri Ulu Langat palm oil mills) in the figure.

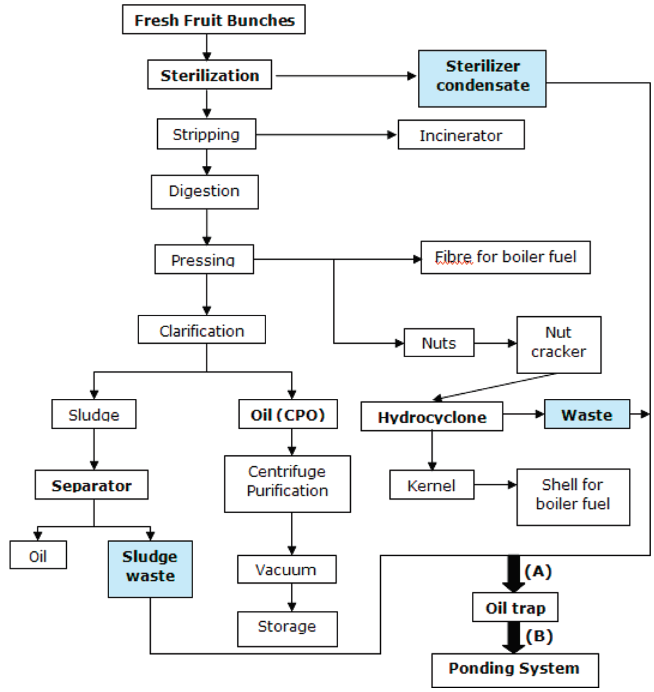

Figure 1. Schematic diagram of a typical palm oil milling process, the sources of POME, and sampling points for the characteristic study. Colored boxes show the sources of POME.

Table 4. Analyzed Parameters for the Characterization of POME

on-site param	off-site param	
pH	BOD_3	TKN
temp	COD_{Cr}	NH_3-N
volumetric flow rate	BOD/COD ratio	TP
appearance	TS	TOC
	SS	O&G
	dissolved solids (DS)	VFA
	TVS	sulfate content
	VSS	lignin
	TN	toxicity

2.2. Parameters for POME Characterization. 2.2.1. On-Site Sampling. On-site sampling was conducted twice for Golconda palm oil mill where once was at low crop season (January 2008) and the other was conducted at high crop season (June 2009). The sampling for Bukit Kerayong and Seri Ulu Langat palm oil mills were conducted at high crop season (July−August 2009). The on-site sampling period for each mill was 1 month. Eight grab samples were taken daily (1 per hour) to form a composite sample.

2.2.2. Parameters and Methodologies for POME Characteristic Study. Table 4 shows the full list of parameters for the characterization of POME, while the methodologies for each of the analyzed parameters in the POME characteristic study were listed in Table 5. The analyses of parameters for characterization were done in triplicate for each sample.

For POME discharge with open drainage systems (i.e., Golconda and Seri Ulu Langat mills), the volumetric flow rate was measured by

$$Q_v = A\frac{d}{t}$$

Table 5. Methodologies Employed for Parameters Analyzed in the POME Characteristic Study

parameters	methodology
BOD_3	3 day BOD test at 30 °C
COD_{Cr}	HACH method 8000[a]
sCOD	HACH method 8000 (filtered sample)[a]
BOD/COD ratio	
TS	APHA 2540 B
TVS	APHA 2540 G
DS[b]	
SS	HACH method 8006 (Photometric)
VSS	APHA 2540 E
TN	HACH method 10072
TKN	HACH Nessler's method 8075
NH_3-N	HACH Nessler's method 8038
TP	HACH total phosphorus method 10127
TOC	HACH method 10128
O&G	APHA 5220 B
VFA	APHA 5560 D
sulfate content	HACH SulfaVer 4 method 8051
lignin	HACH tyrosine tannin/lignin method 8193
toxicity	HACH method 10017

[a] HACH methods that comply with the APHA standard methods. [b] DS is calculated on the basis of the following formula: DS (mg/L) = TS − SS.

where Q_v = volumetric flow rate (m^3/s), A = cross-sectional area of the open channel (m^2), d = distance traveled by the float (m), and t = time taken for the float to travel a distance, d (s).

Since the flow rate of POME for Bukit Kerayong palm oil mill could not be measured directly due to the closed piping design, an estimation of the flow rate is made on the basis of the daily CPO production figures provided by the mill.

3. Results and Discussion

3.1. Comparison of POME Characteristic between Low and High Crop Seasons. Table 6 lists the characteristics of POME for Golconda palm oil mill during low and high crop seasons. Not all parameters as listed in Table 6 were selected for comparison of POME characteristics from Golconda palm oil mill at low crop seasons. Only parameters that were most often discussed in the literature were tested, and this will enable a direct comparison to the literature values as listed in Table 2. The POME characteristics for Golconda palm oil mill at low crop season corresponded to the literature values by Ma and Ong,[4] Ahmad et al.,[5] MPOB,[6] and Zinatizadeh et al.,[7] while the high crop season characteristics were similar to the values published by Choorit and Wsarnwan,[8] Wu et al.,[9] Oswal et al.,[10] and Zhang et al.,[11] as listed in Table 2.

The measured pH 4.4 at low crop season was found to be only slightly lower than the pH measured at high crop season, which was recorded at pH 4.7. This is the only parameter which remained almost constant regardless of the change of the season. During the high crop season between June to November every year, the plant operates at its maximum capacity with 30 tons of FFB processed every day. Corresponding to this capacity, the average flow rate of POME measured in this study during high crop season was evidently higher, which was recorded at 40.4 m^3/h. This was double the flow rate during the low crop season between November to May, measuring at 20.0 m^3/h when the plant processes 20 tons of FFB daily. This large difference in flow rates between low and high crop season shows the importance of conducting a comprehensive POME characteristic study, especially when the mill is operating at its maximum capacity. A characteristic study showing the maximum limit of the measured parameters would ensure the proper process design and equipment sizing so that the treatment plant will not be operated over its designed capacity during the high crop season. This is especially critical for the treatment system of POME as the result from Table 6 showed that the characteristics of POME during high crop season for Golconda palm oil mill deviated at approximately ±20−50% from the values recorded during low crop season.

Besides discharging at higher flow rates during the high crop season, the POME was evidently more concentrated and thicker as most of the measured parameters had considerably higher concentrations as compared to those measured at the low crop season. BOD concentration in POME at high crop season (54 400 mg/L) was almost twice the BOD concentration of POME at low crop season (29 000 mg/L) while the COD concentration at high crop season (73 900 mg/L) was approximately 1.3 times of the COD concentration at low crop season (57 000 mg/L). The BOD and COD values obtained at

Table 6. Characteristics of POME from the Three Sampled Palm Oil Mills and the General Characteristics of POME[a]

			high crop season							
	low crop season (Golconda)		Golconda		Bukit Kerayong		Seri Ulu Langat		general POME characteristics	
param	av	std dev	av	std dev	av	std dev	av	std dev	av	std dev
temp (°C)	56	±4.71	47	±4.52	63	±6.00	61	±6.26	57.1	±13.27
pH	4.4	±0.03	4.7	±0.19	5.4	±0.19	4.5	±0.26	4.86	±0.64
flow rate (m^3/h)	20.0	±12.72	40.4	±15.15	23.8	±11.92	41.5	±30.02	36.9	±29.81
BOD (mg/L)	29 000	±11 927	54 400	±18 198	51 100	±7206	41 900	±9381	49 000	±27 457
COD (mg/L)	57 000	±19 578	73 900	±1970	84 200	±3558	80 400	±7617	79 000	±10 803
sCOD (mg/L)	31 000	±7416	34 100	±1331	36 700	±645	37 900	±2022	36 200	±4307
BOD/COD	0.51	±0.32	0.74	±0.24	0.61	±0.06	0.52	±0.10	0.62	±0.38
SS (mg/L)	20 000	±7826	20 100	±1334	28 900	±3808	30 800	±4066	39 100	±5060
TS (mg/L)	41 000	±12 591	43 700	±2820	55 200	±4759	57 800	±3699	43 300	±11 335
DS (mg/L)	21 000	±6795	23 600	±2485	26 300	±2794	27 000	±2061	25 600	±5046
TVS (mg/L)	32 000	±11 756	33 800	±2300	51 800	±5207	44 104	±2083	42 600	±12 781
TP (mg/L)	N/A	N/A	872	±213	1510	±196	762	±88	1020	±560
TOC (mg/L)	N/A	N/A	18 600	±1217	34 600	±8671	21 000	±829	24 100	±14 516
O&G (mg/L)	5500	±4814	6100	±1094	26 800	±2713	13 700	±1998	14 700	±12 466
NH_3-N (mg/L)	144	±40	193	±61	21	±4.3	40	±18.5	89	±118
TKN (mg/L)	650	±278	750	±452	775	±481	900	±299	930	±600
TN (mg/L)	N/A	N/A	852	±107	875	±355	968	±326	956	±752
VFA (acetic acid) (mg/L)	1806	±684	3540	±510	1170	±634	471	±240	1800	±1905
SO_4 (mg/L)	N/A	N/A	8	±8.37	5	±10	2	±4	5	±10.41
lignin (mg/L)	N/A	N/A	1680	±151	1600	±143	1740	±118	1700	±225
toxicity (% inhibition)	N/A	N/A	−13.3	±11.95	−51.8	±12	−62.1	±39	−42.0	±34

[a] N/A, data not available.

high crop season were higher than the literature values[4−7] as listed in Table 2.

On the other hand, higher O&G content was obtained during the high crop season. This would have attributed partially to the higher BOD and COD values in the POME during the high crop season. However, the slight increase in the TS, SS, and TVS concentrations during the high crop season indicated that more soluble organic matters could be dissolved in POME from the oil extraction process during the high crop season which led to the higher concentration of COD and BOD. A thicker POME during the high crop season was due to the differences in oil palm fruit characteristics. PORIM[25] discussed on the influence of fruit types on the rate of oil extraction where different variants of oil palm fruits would yield different oil extraction efficiency. Lower oil extraction efficiency from the fruits would cause the increase of O&G concentration in POME.

3.2. POME Characteristics from Three Sampled Mills. The results of POME characteristics during low crop season agreed with the majority of the published characteristics of POME. Characterization of POME at high crop season is crucial as the knowledge acquired from the characterization study at its maximum limits would enable a proper design of treatment plants. Therefore, sampling of POME from three different mills was only conducted at high crop season to study the difference in POME characteristics between the three mills at high crop season. A complete characteristic study which comprises other parameters that were not often quantified previously was conducted to enable the evaluation of the suitability of anaerobic treatment for POME treatment. The POME characteristic obtained in the present study can also serve as a reference to other POME related study. Table 6 shows the characteristics of POME for Golconda, Bukit Kerayong, and Seri Ulu Langat (Dengkil) palm oil mills which were sampled at high crop season. In comparison with the literature values listed in Table 2, the POME characteristics of the three sampled mills were relatively more concentrated compared to most of the literature values. Nevertheless, these values fall into the range of POME characteristics sampled by Choorit and Wisarnwan.[8]

The discharge temperature of POME in Golconda palm oil mill was found to be lower than the rest of the two mills. The sampling location and the retention time of POME in the oil trap would be the two major factors which caused the difference of the discharge temperature for POME in Golconda palm oil mill.

The O&G content for POME obtained from Bukit Kerayong palm oil mill was unexceptionally high as compared to the other two mills, and this was due to the difference in sampling locations of POME. Because the POME from Bukit Kerayong palm oil mill was collected before the oil trap, the sample would have contained more O&G as compared to the other two mills. Hence, the O&G content in POME was very much influenced by the sampling point of POME.

From Table 6, it can also be observed that the TP content in the POME obtained from Bukit Kerayong palm oil mill was higher than those from Golconda or Seri Ulu Langat (Dengkil) palm oil mill. The higher concentration of phosphorus would be partially due to the presence of a high amount of phospholipids, which was also reflected in terms of a high concentration of O&G in the POME of Bukit Kerayong palm oil mill. Further classification tests on individual phosphate components (i.e., orthophosphate, methaphosphate, and organic phosphate, etc.) should be conducted in future studies on POME to study the distribution of phosphate components in POME. This would enable a better understanding of the phosphate distribution in POME and a better proposal for efficient phosphate removal in POME.

Overall, most of the parameters of POME sampled from the three mills showed consistent average values, with no drastic deviations observed except for the O&G content, ammoniacal nitrogen (AN) content, and volatile fatty acid (VFA) content. The significant difference in these values indicates the degree of degradation of POME when it was sampled, where high values of AN and VFA showed higher degree of degradation and vice versa.

3.3. POME Characteristics and Its Impact on Anaerobic Digestion. Table 6 also shows the overall characteristics of POME which were obtained on the basis of the characteristics studies conducted at Golconda, Seri Ulu Langat, and Bukit Kerayong palm oil mills during the high crop season. Parameters of POME that were analyzed were significantly higher at high crop season due to higher production capacity. It is reasonable to adopt the data at high crop season as the most updated POME characteristics for general reference because it will provide a practical value that can be used for process design and equipment sizing for POME treatment systems.

The general POME characteristics in Table 6 were in agreement with the POME characteristics study conducted by Choorit and Wisarnwan[8] except for the higher O&G concentrations due to the difference in sampling points. This would imply that the POME characteristic study carried out by Choorit and Wisarnwan[8] was conducted during high crop season, while the other researchers[4−7] as in Table 2 had conducted their studies during low crop season.

Table 6 shows that the average discharge temperature of POME is at 57.1 °C, which was lower than literature values. This could be attributed to by a few factors depending on the configuration of the palm oil mills. The location of the sampling point which has been specified under DOE regulation is one of the causes for the lower temperature. A longer distance between the original POME discharge point and the sampling point specified under DOE regulation implies that POME has to travel a longer distance before sampling and more heat will be dissipated to the surrounding, causing the lower temperature of POME. The advancement of current technology such as vertical sterilizers is the other cause for lower POME temperature.[26] The use of vertical sterilizers reduces the amount of steam required for the sterilization of FFBs as compared to horizontal sterilizers, and this will in turn lower the overall temperature of POME as the temperature of the POME discharged from the sterilizer condensate will be lower due to the lower amount of steam required. Nevertheless, the discharge temperature implied that anaerobic treatment of POME in either mesophilic or thermophilic condition is possible. Cail and Barford[27] showed that the anaerobic digestion rate at thermophilic conditions was four times faster than the digestion rate at mesophilic conditions. The methane production rate and COD reduction efficiency was also higher at thermophilic conditions.[28] Operation of anaerobic POME treatment in the thermophilic condition will also prevent clogging of pipes and inhibition of anaerobic digestion due to high O&G concentration. At higher temperatures, the formation of granular sludge will not be inhibited by high O&G concentration (>3000 mg/L), and at the same time, a higher rate of acidogenesis enables higher conversion of O&G, which is harmful to a large number of bacteria.[22] This will thus increase the conversion of methane, provided that the level of acetic acid is maintained at a suitable level (i.e., propionic acid to acetic acid ratio of less than 1.4) to prevent failure of the bioreactor.[29]

Therefore, on the basis of the characteristic of POME, anaerobic treatment of POME at thermophilic temperature could be another viable option.

The BOD/COD ratio indicates the ability of a wastewater being treated biologically.[30] Table 6 shows that the BOD/COD ratio for POME is 0.5 or above, and this indicates that POME is suitable to be treated by biological means. A typical high-strength wastewater has BOD or COD concentration which is more than 10000 mg/L.[31] The high COD and BOD values recorded throughout the sampling period in all mills as shown in Table 6 indicated that POME is considered a high-strength wastewater, and thus an anaerobic system could be the most feasible option.[30] Aerobic treatment which uses aeration is not economical even for the treatment of POME at the lowest recorded COD concentration of 57 000 mg/L during the low crop season. The energy as high as 10.83×10^6 kJ/day is required to aerate the POME at the COD concentration of 57 000 mg/L on the basis of the assumption of 0.8 kg of oxygen required/(kg of COD removed) with an aeration efficiency of 1.52 kg of O_2/kWh.[24] As such, twice as much energy will be required during the high crop season with the maximum attainable COD of 90 000 mg/L for aeration, which is again proven not to be feasible. In addition to the increase in fuel prices besides its impact on energy and environmental conservation, aerobic treatment with high energy consumption is not the suitable option. Furthermore, anaerobic treatment produces less biological sludge, requires lower nutrient consumption during operation, and produces biogas for energy, making it to be the feasible option.[30] Total organic carbon provides a measure of the concentration of organic carbon present in the wastewater. The TOC content in POME was found to be 24100 mg/L, which is considerably high. This implies that POME contains a large amount of carbon-bearing molecules, and since POME constitutes a large amount of biodegradable components, the level of organic carbon in POME could be reduced by treating it anaerobically with high-rate bioreactors.

The total volatile solids content in POME ranged between 31 140 and 56 660 mg/L, and this accounted for approximately 76% of the total solids content (39 800−60 940 mg/L). A high amount of TVS in POME will not lead to any inhibition and offset toward the anaerobic digestion of POME as higher TVS shows a higher biodegradability of the wastewater.[32]

A suitable ratio of macronutrients for the growth of microbes in anaerobic systems was given in terms of COD:N:P of 250:5:1.[33] The average COD, TN, and TP values obtained from this study were 79 000, 900, and 1020 mg/L, respectively. On the basis of the characteristics obtained in this study, the ratio of COD:N:P of POME was 250:2.9:3.2. On the basis of the recommended COD:N:P ratio for growth of microbes, the ratio of COD to N in POME was lower than the nominal value while the concentration of P was in excess. Besides indicating that POME had sufficient phosphorus concentration for the growth of microbes, the high phosphorus concentration indicated that POME has to be treated before discharge because direct discharge could potentially lead to eutrophication of watercourses. So far, no issues have been reported on anaerobic treatment of POME due to insufficient or oversupply of nutrients. This implies that POME can still be treated anaerobically although the COD:N:P ratio of POME differs from the recommended ratio stated in the literature. Longer retention time might be permissible during the anaerobic treatment of POME to allow for a higher degree of utilization of excessive nutrients in POME while supplements of nitrogeous compound can be added to adjust the ratio of COD to N to the recommended ratio for effective microbial growth. The average TKN and AN concentrations for POME are 930 and 89 mg/L, respectively. High TKN and low ammoniacal nitrogen concentrations indicated that POME contained a high amount of organic nitrogen which also indicated the high biodegradability of POME.

The concentrations of suspended solids and O&G in POME are 39 100 and 14 700 mg/L, respectively. Jeganathan et al.[34] shows that at least 90% of O&G can be removed from an initial concentration of 23 000 mg/L in the treatment of oily wastewater by using a packed bed reactor and upflow anaerobic sludge bed reactor with suitable OLRs at mesophilic temperature. The SS content in the oily wastewater was 39 000 mg/L, which was similar to the SS concentration in POME. Furthermore, the volatile fraction of SS was 84% of the total SS content, again proving the biodegradability of these solids in POME. As such, the amount of suspended solid and O&G should not pose any operational problems such as clogging, scum formation, or inhibition of granular sludge formation when POME is treated anaerobically using high-rate bioreactors by manipulating the HRT to allow longer contact between solids and biomass for hydrolysis of SS in POME.[35]

The pH of POME is another concern in the application of anaerobic digestion on the treatment of POME. Volatile fatty acids (i.e., acetic acid, propionic acid, etc.) and isobutyl alcohol contribute to the acidity of POME[3] besides the O&G content. Table 6 shows that POME is acidic with values between 4.4 and 5.5, which was very much lower than the optimum of pH 6.8−7.2 for methanogenesis[22] in anaerobic digestion. The pH value in the operation of an anaerobic digestion system is crucial for the growth of microbial consortia and methanogenesis as they will be inhibited when the pH of the anaerobic system is less than 6.2.[22] Therefore, the maintenance of pH using sodium bicarbonate or potassium bicarbonate in the anaerobic digestion system is very important,[22] which will act as the buffer in the digestion process. Another alternative to avoid digester upset is the maintenance of pH and its alkalinity through the recirculation of treated effluent back into the system. This will also enable the digester to cater to a higher concentration of VFA (>2000 mg/L) without inhibition of methanogenesis as long as the pH of the digester is maintained at its optimum range.[36] The average concentration of VFA in POME was 1800 mg/L, which is lower than the 2000 mg/L limit of VFA, which would cause inhibition to conversion of methane. Hence, POME can be treated anaerobically with adequate monitoring of the VFA level in the anaerobic bioreactor. Furthermore, the inhibitory effect due to a high concentration of VFA can be rectified through the increase in the alkalinity level or by reducing the organic loading rate in the digester.

Toxicity is the degree to which a substance will damage an exposed organism. The toxicity of POME was found to be −42%, which indicates that POME is harmful to living organisms. As such, direct discharge is not permissible. However, a toxicity test only indicates the relative measurement of toxicity, and analyses of individual toxic components have to be undertaken to obtain a quantitative value on the toxicity in POME. POME has an average sulfate concentration of 5 mg/L. This would not lead to build up of the toxicity level during the anaerobic digestion of POME through the reduction of sulfate ions to form sulfide ions which are toxic. As such, the toxicity caused by reduction of sulfate ions will not pose a threat to anaerobic POME treatment systems.

Anaerobic treatment of POME with high-rate anaerobic bioreactors was unable to achieve satisfactory treatment efficiency before the anaerobically treated effluent was being

Table 7. Parameters for the Operation of Anaerobic POME Treatment System at Thermophilic Condition

param	value/range
POME Characteristics	
BOD (mg/L)	49 000
COD (mg/L)	79 000
SS (mg/L)	39 100
O&G (mg/L)	14 700
Operating Conditions	
temp (°C)	55.0
pH	6.8−7.2
HRT (days)	1−4
OLR (kg of COD/(m^3 day))	12.5−50.0
COD:N:P	250:2.9:3.2
MLSS (mg/L)	10 000[24]
Treatment Efficiencies[39]	
COD removal	>90%
methane concentration	>60%

polished with an aerobic system to a level which was suitable for discharge. Though the final treated effluent meets the standard effluent discharge limit, it still remains as a clear brownish solution. To date, only membrane treatment systems were able to remove the color completely, but the treatment cost will be expensive.[13] This is possibly due to the presence of the lignin compound in POME which is difficult to digest and the intermediate products from the degradation of lignin contributed to the brownish color in the wastewater.[23,37] On the other hand, Table 6 shows that POME contains a high amount of lignin with concentrations between 1450 and 1900 mg/L. Nonetheless, Wu et al.[38] has proven the feasibility of lignin removal through white-rot fungi, while Singh and Thakur[37] showed that color can be removed by *Paecilomyces* sp. and *Microbrevis luteum*. As such, anaerobic treatment still remains as an attractive option for POME treatment as it can be integrated with aerobic digestion which can be inoculated with white-rot fungi or other lignin and color removal bacterial strains to improve the quality of the final treated POME for discharge.

High-rate anaerobic bioreactors are the better options as compared to the conventional ponding systems and other POME treatment systems as it is able to cope with the variation of POME characteristics throughout the low and high crop seasons. OLR of the bioreactor can be manipulated according to the feed variations to achieve the desired COD removal efficiency. The high-rate anaerobic bioreactors allow a high influent feed concentration of POME, especially during high crop season, by increasing its OLR to maintain HRT similar to that for low crop season because the increase of OLR values to its optimum allowable value would lead to improved COD removal efficiency. During the occasions of higher SS concentration, OLR or HRT can also be manipulated to allow POME with higher solid content to be in contact with the active biomass for a longer period of time for hydrolysis of SS in the system.[35]

Therefore, POME is suitable to be treated anaerobically, and Table 7 summarizes the recommended values for the operation of an anaerobic POME treatment system at thermophilic condition based on the typical POME characteristics found in this study and through the study of a batch continuous stirred-tank reactor in the treatment of POME under thermophilic conditions.[39] In the operation of the anaerobic system under thermophilic condition, it is vital to ensure that the MLSS concentration in the system is adequate for successful start-up and operation of the bioreactor. Another concern in the operation of anaerobic treatment of POME is the pH and the alkalinity of the system. The pH has to be kept in the range between 6.8 and 7.2 to prevent reactor upset due to accumulation of VFA. Buffer has to be supplied to the system if the alkalinity of the system is inadequate in order to ensure that the system has the ability to cope with the pH decrease caused by the production of VFA.

3.4. Clean Development Mechanism on Anaerobic Treatment of POME. CDM allows developing countries to earn certified emission reduction credits by implementing sustainable emission reduction projects. These CER credits can be used by developed countries to achieve their emission reduction targets and, at the same time, developing countries obtain CER as revenue. CDM provides the advantage to developing countries such as Malaysia to attract foreign investments on renewable energy projects.[40]

The CER credits encourage anaerobic POME treatment by using a high-rate digester as it enables a shorter payback period. An annual income of € 216 520 is expected from a CDM project based on the amount of methane captured from open digesting tanks for POME treatment, whereby a total of 21 652 tons of CO_2 equivalent was emitted from six open digesting tanks per annum.[24] An estimation on the income that could be generated through a CDM project was calculated on the basis of a laboratory-scale UASFF bioreactor studied by Najafpour et al.[33] which has been scaled up to 5000 m^3. It was found that for a 97.5% removal and a methane yield of 0.344 L of CH_4/(g of $COD_{removed}$), 58 210 tons of CO_2 equivalent could be generated per annum, thus leading to an income of € 582 100. Calculations were done on the basis of 273 working days and CER credits of €10/(ton of carbon emission reduction). This comparison shows that the use of high-rate digesters could generate an income twice as much as the income from conventional treatment methods if the anaerobic treatment of POME with a high-rate digester was registered as a CDM project. The current price of CER credits ranges from €12 to €16/(ton of carbon emission reduction);[41] thus it is expected that larger income could be generated through the registration of anaerobic POME treatment systems as a CDM project. A survey conducted by Point Carbon[41] indicated that 83% of survey correspondents forecasted that CER demand will be likely or very likely. It is also expected that the CER credit will rise to €24 by year 2010.[42] Furthermore, it is expected that the United States will be gearing up for massive carbon trading in the future as the president of the U.S. promises deep emission cuts in the country and vigorous climate diplomacy internationally.[41] Therefore, the increasing demand in CER will encourage the development of anaerobic digestion of POME using the high-rate bioreactors due to its pardigm shift from a nonprofiting treatment plant to a profitable yet energy sustainable process besides preserving the environment.

Currently, the demand of CERs is greater than its supply, with 348 400 729 CERs demanded and 335 319 007 CERs supplied.[43] Various companies and organisations have set up carbon funds to aid the CDM projects' implementation. For instance, KfW Carbon Fund purchases emission credits from CDM projects and sells the credits to buyers in need to reduce carbon emissions. World Bank Prototype Carbon Fund invests money contributed by governments and companies to purchase green house gases emission reductions from developing countries. The Danish government set up a facility (Danish CDM Project Development Facility) which acts as a direct buyer of CERs as well as providing project follow-up services. This will facilitate the palm oil mills to look into the application of anaerobic POME treatment system by using high-rate bioreactors as a CDM project to earn CERs. Currently there are 10 projects on recovery and usage of biogas produced from POME treatment registered under CDM.[44]

The accreditation of SIRIM QAS International Sdn. Bhd. in Malaysia as the designated operational entity allows the process of registering a CDM project in the country to be more efficient. Palm oil mills in Malaysia, in this case, will benefit in terms of the costs required to validate, verify, and certify a project for CDM project registration, which is always a minus factor that discourages palm oil mills to implement anaerobic POME treatment systems.

CDM is the major factor which attracts palm oil mills to invest in an anaerobic POME treatment system using high-rate bioreactors due to the lucrative revenue earned from CERs. It is expected that more anaerobic POME treatment projects will register under CDM due to the monetary assistance offered by various organizations and the successful implementation of a registered anaerobic POME treatment system under CDM.

4. Conclusion

Characteristic study of wastewater is essential in the industry as it provides data on design parameters that could be extracted for the design or modification of industrial-scale WWTP, and it is less time- and cost-consuming as compared to obtaining design parameters from laboratory- or pilot-scale studies. On the basis of the POME characteristics study conducted here, it can be concluded that characteristic study of POME has to be conducted at its maximum limit of discharge to ensure proper process design and equipment sizing due to a variation of ±20−50% from the values of low crop season. The general POME characteristics obtained from this study supported the fact that POME is suitable to be treated anaerobically despite some of the undesired factors that will cause problems to the operation. The development of technology in anaerobic wastewater treatment and suitable modification to the anaerobic digesters will eliminate operating problems due to undesired factors such as high suspended solids or O&G concentration. Furthermore, the introduction of CDM and formation of carbon funds encourages palm oil mills to implement anaerobic POME treatment following the success of palm oil mills that registered anaerobic POME treatment system as a CDM project.

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