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NUMAN ABDUL HADI[1], YAHAYA HAWARI[1], MUZZAMMIL NGATIMAN[1],
NOR FAIZAH JALANI[1], NOORSHAMSIANA ABDUL WAHAB[1], ROHAYA MOHAMED HALIM[1]

ASSESSMENT OF THE EFFLUENT POLISHING PLANT USING A ULTRAFILTRATION MEMBRANE INSTALLED AT A PALM OIL MILL

Palm oil mills discharge raw effluent with high biochemical oxygen demand (BOD) of about 25 000 mg O_2/dm^3. Conventional effluent treatment system uses ponds with a long hydraulic retention time of about 55–85 days, but the reduction of BOD is usually halted at 100–250 mg O_2/dm^3. Further reduction of BOD to below 20 mg O_2/dm^3 to meet regulation requirement needs further advanced treatment. This study evaluates the efficiency of an effluent polishing plant installed at a palm oil mill targeting final effluent BOD below 20 mg O_2/dm^3. Characteristic of the incoming and treated effluent, dissolved oxygen in the aeration ponds and the effluent flow rate of the treatment plant have been determined. Due to low process throughput at the mill, the polishing plant operated at only 60% of its designed capacity. Treatment of effluent showed reduction of BOD from 39.3±5.8 to 6.1±3.8 mg O_2/dm^3, i.e., a reduction by 80–94%. Colour – a newly proposed regulation parameter – was reduced from 1081±69 to 845±60 ADMI, i.e., by 11–30%. This study indicates that while the treatment of effluent to reduce the BOD to below 20 mg O_2/dm^3 is feasible, reduction of colour to less than 100 ADMI is not achievable.

1. INTRODUCTION

Regulations on environment issues for Malaysian palm oil mills have always been debated among the palm oil industry players. Parties directly involved in the environmental issues related to palm oil mill are the millers, local authority bodies, government research bodies and non-government organisations. Stringent regulations are being implemented on palm oil mills following the rapid growth of crude palm oil (CPO) production. Malaysia produced 17.32 million t of CPO in 2016, an enormous amount compared to 92 000 t of CPO produced in 1960 [1, 2].

[1]Engineering and Processing Research Division, Malaysian Palm Oil Board, 6, Persiaran Institusi, Bandar Baru Bangi, 43000 Kajang, Selangor, Malaysia, corresponding author N. Abdul Hadi, e-mail address: numan@mpob.gov.my

Large amount of palm oil mill effluent (POME) is being generated following the production of CPO. For every 1 t of CPO produced, 2.5–3.75 t of POME will be generated. 43.3–65.0 million t of POME was generated in 2016 [3, 4]. Untreated POME contains high amount of organic matter that rapidly depletes dissolved oxygen in water bodies; therefore it is regarded as a major source of pollutant to river streams [5].

In Malaysia, palm oil mills are required to treat POME until its biochemical oxygen demand (BOD) is lower than 100 mg O_2/dm^3. Table 1 shows the standards set by the Malaysian Department of Environment (DOE) under the Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 [6]. The DOE has been revising the BOD limit from 5000 mg O_2/dm^3 in 1978 to 100 mg O_2/dm^3 in 1984 [6]. Recent development in 2015 was that new standards were proposed with a BOD limit of 50 and 20 mg O_2/dm^3 in stages, as shown in Table 1 [7]. Furthermore, colour was also proposed as a new regulated parameter, measured in ADMI (American Dye Manufacturing Institutes) unit usually applicable in the textile industry [7–9]. However, for Sabah (a state in Malaysia), BOD limit of 20 mg O_2/dm^3 coupled with land irrigation has been imposed for new mills and mills located along the three main rivers [10].

Table 1

Parameter limits for watercourse discharge and the new proposed standards for palm oil mill effluent

Parameter[a]	January 1st, 1984 –June 30th, 2016	July 1st, 2016 –December 31st, 2019	January 1st, 2020 and thereafter
BOD, mg O_2/dm^3	100	50	20
SS, mg/dm^3	400	200	200
OG, mg/dm^3	50	5	5
AN, mg NH_3-N/dm^3	150	20	20
pH	5–9	5–9	5–9
Temperature, °C	45	45	45
Colour, ADMI	–	100	100

[a]BOD biochemical oxygen demand, SS suspended solids, OG oil and grease, AN ammonia nitrogen.

Conventional treatment of POME in palm oil mill requires a series of biological processes: anaerobic, facultative and aerobic ones, usually referred to as ponding or secondary system [11]. The anaerobic digestion of POME reduces the BOD from ca. 25 000 to 1000–1500 mg O_2/dm^3, which is about 95% BOD reduction. Facultative and aerobic processes further reduce the BOD to less than 100 mg O_2/dm^3 [11]. More stringent regulation proposed by the DOE requires further treatment of POME in the tertiary treatment system or effluent polishing plant to achieve POME BOD of less than 20 mg O_2/dm^3.

Ponding system requires frequent cleaning through a desludging process – a practice to reduce solid accumulated at the bottom of ponds [11]. It is sometimes called the primary treatment system. Desludging is conducted by excavating a thick layer of

POME from the anaerobic or facultative pond and transferring it to another empty pond. The wet solid will be left to dry naturally. In a few mills, dewatering system such as decanters and belt press is used to separate the liquid from the solid phase. The solid is disposed-off on land or dried in a rotary drier to be used as fuel and fertiliser [12].

Several authors reported the treatment of POME in various types of treatment systems. This includes sequencing batch reactor (SBR), activated sludge process and membrane ultrafiltration [13–17]. SBR is one of many conventional treatment systems which is operated based on a timely cycles – fill, react, settle and decant – to facilitate the aerobic process through aeration, settlement of solids and the removal of suspended solids [18]. A laboratory scale SBR unit reported a maximum BOD reduction of 97–98% for the treatment of anaerobically digested POME while maintaining pH and dissolved oxygen at 8.29–9.14 and 1.5–6.4 mg O_2/dm^3, respectively [13]. The SBR process is versatile and can sustain high fluctuation in organic loadings, but can hardly retain the effluent BOD below 20 mg O_2/dm^3 [19].

Aerobic treatment of POME using activated sludge process has been reported by Vijayaraghavan et al. [15]. The effect of sludge volume index, scum index and mixed liquor suspended solid (common parameters monitored in the activated sludge process) on the COD removal was studied. The anaerobically digested POME and diluted raw POME were treated by varying hydraulic retention time (HRT) at 18, 24, 30 and 36 h. A maximum of 84% COD removal for the treatment of diluted raw POME having COD of 4000 mg O_2/dm^3 after 36 h of HRT was observed. Only 27% of COD removal was reported after the diluted raw POME having COD of 4000 mg O_2/dm^3 was treated for 24 h. About 93% of BOD removal was reported as well, bringing down effluent BOD from 1720 to 120 mg O_2/dm^3 [15].

The main objective of this study was to assess the POME polishing plant installed at a palm oil mill in Sabah, Malaysia to achieve final effluent BOD of less than 20 mg O_2/dm^3 consistently. The assessment is conducted considering the palm oil mill operating condition, ponding system, design of the polishing plant and analysis of effluent characteristics in terms of biochemical oxygen demand, suspended solid, oil and grease, ammonia nitrogen and pH. This assessment also aimed to determine the effect of the polishing plant treatment on colour reduction for the treated effluent.

2. EXPERIMENTAL

Palm oil milling activity and ponding system. The assessment was carried out in the local palm oil mill with polishing plant system for the treatment of the POME. Information related to palm oil milling process, overall POME treatment system and design specifications of the POME polishing plant was gathered. This includes amount of CPO produced, amount of final effluent discharged, HRT of ponding system and type of polishing plant.

Sampling procedures. Sampling was carried out at the POME polishing plant. 1 dm^3 samples at the inlet (influent) and outlet (effluent) were collected for the period of 12 days, sealed in an air-tight plastic bottle and kept refrigerated below 4 °C. Two types of sampling were introduced, namely grab sampling and composite sampling. The former refers to the samples taken after 2 h of plant operation, while the latter refers to the samples taken in the interval of 1 h, 3 times daily, where the samples were further homogeneously mixed to represent 1 sample.

Monitoring of the polishing plant activity. Besides analyses of samples, polishing plant monitoring activities namely the dissolved oxygen, pH and temperature at bioreactor pond, number of active aerators, amount of discharged sludge, amount of returned sludge, influent flow rate and effluent flow rate were also recorded. The following analyses were carried out on the collected samples: biochemical oxygen demand (BOD), suspended solid (SS), oil and grease (OG), ammonia nitrogen (AN), pH and colour. BOD, SS, OG and AN were determined in accordance with the standard methods published by the Department of Environment of Malaysia [20]. Measurement of biochemical oxygen demand was based on 3 days incubation at 30 °C. Colour was determined in accordance with the standard method published by the American Public Health Association (APHA) [21]. pH was determined using a Hanna microprocessor pH/mV meter (Woonsocket, United States).

3. RESULTS AND DISCUSSION

3.1. CHARACTERISTICS OF THE MILLING PROCESS AND POME TREATMENT SYSTEM

Table 2 shows the data related to the actual milling activity and overall POME treatment system. In 2016, the mill processed a total of 151 548 t of palm fresh fruit bunches (FFB), which is about 42% of the mill's total FFB processing capacity.

Table 2

Parameters for crude palm oil production and ponding system

Parameter	Value
FFB processing capacity, t/year	360 000
FFB processing license, t/year	340 00
Actual FFB processed in 2016, t	152 548 t
Desludging activity	continuous, decanter
Decanter feeding source	anaerobic pond
Desludging feeding rate, m^3/h	20.5
Number and HRT of cooling ponds	2 (2 days)
Number and HRT of anaerobic ponds	5 (215 days)
Number and HRT of aerobic ponds	3 (103 days)
Treated effluent discharged in 2016, m^3	101 916

Ponding system was used to treat the mixed raw POME, coupled with a dewatering system to reduce solids in the POME. The ponding system consists of 10 ponds, equivalent to 320 days of HRT. The POME is then further treated in the polishing plant with targeted final effluent BOD of less than 20 mg O_2/dm^3. Amount of treated effluent discharged in 2016 was about 101 916 m^3, or approximately 67% of the total FFB processed.

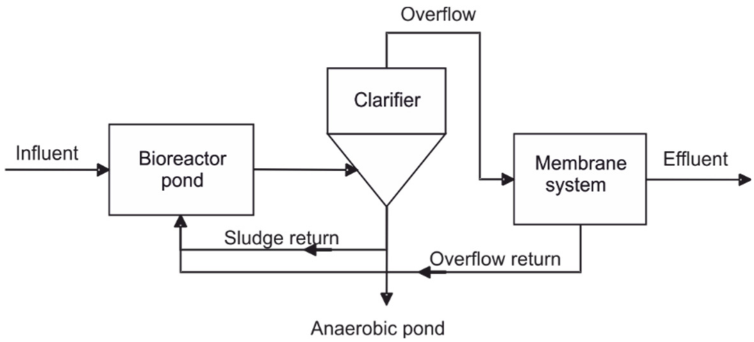

Fig. 1. Process flow for the treatment of POME at the polishing plant

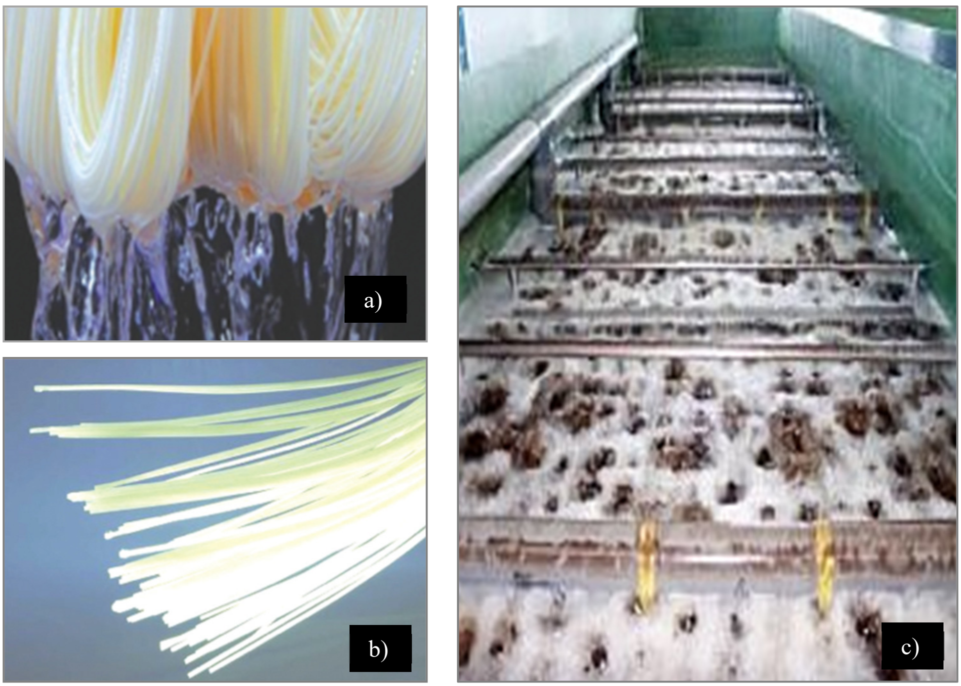

Fig. 2. Polyvinylidene-fluoride-hollow-fibre membrane (a, b),
and submerged membrane modules in an aerated skid tank (c) [16]

Process flow for the treatment of POME in the polishing plant is shown in Fig. 1. The polishing plant consists of three stages, involving biological and physical processes. The POME was pretreated through the aeration process in a bioreactor pond in order to keep the dissolved oxygen at 2–5 mg O_2/dm^3. Consistent oxygen supply is necessary to facilitate aerobic bacterial activity in the pond. The settlement of the suspended solid occurs at the clarifier where the solid-rich sludge is continuously removed. Hollow-type ultrafiltration membrane is used to further treat the POME coupled with extended aeration. The membrane system is incorporated with polyvinylidene-fluoride-hollow-fibre submerged membrane modules with outside-in filtration technology as shown in Fig. 2. The designed parameter for influent BOD and effluent BOD is 200 mg O_2/dm^3 and 20 mg O_2/dm^3, respectively. The designed capacity of the polishing plant is 70 m^3/h of POME.

Table 3

Characteristics of influent and effluent at the polishing plant

Day	BOD [mg O_2/dm^3]	SS [mg/dm^3]	OG [mg/dm^3]	AN [mg NH_3-N/dm^3]	pH	Colour [ADMI]
Influent						
1	36.9±0.6	48±4	nd	42.0±0.6	8.6	1035±15
2	37.0±1.5	56±5	nd	43.1±1.1	8.5	985±45
3	35.0±1.1	20±7	nd	46.2±1.4	8.1	1035±10
4	42.2±2.6	32±1	nd	45.6±1.4	8.4	1045±5
5	37.4±7.5	34±9	nd	35.9±6.2	8.2	988±18
6	50.5±1.4	52±6	4	44.3±0.5	8.4	1070±55
7	47.7±3.5	54±2	3	44..8±0.0	8.0	1095±20
8	10.9±0.6	41±2	nd	45.9±0.0	8.4	1130±0
9	42.9±1.7	60±2	nd	44.8±0.0	8.3	1118±13
10	33.4±3.0	57±2	nd	51.4±0.0	8.4	1178±8
11	33.5±2.9	56±1	3	51.4±0.0	8.0	1163±23
12	36.1±0.8	42±1	4	54.3±0.0	8.3	1138±13
Effluent						
1	2.9±0.2	7	nd	2.8±0.6	8.7	760±0
2	2.3±0.0	nd	nd	1.1±0.0	8.6	690±10
3	5.4±0.2	nd	nd	1.4±0.0	8.6	813±8
4	5.2±1.4	nd	nd	1.1±0.0	8.7	848±23
5	7.4±0.4	nd	nd	2.1±0.1	8.4	875±5
6	5.2±0.5	nd	nd	1.9±0.2	8.6	883±3
7	4.5±0.3	nd	nd	2.8±0.6	8.4	855±15
8	16.0±0.7	nd	nd	1.6±0.2	8.7	905±0
9	8.3±0.6	nd	nd	2.1±0.1	8.6	855±5
10	4.4±1.5	nd	nd	2.8±0.2	8.6	855±5
11	5.3±0.3	nd	nd	2.2±0.2	8.6	885±5
12	6.1±0.3	3	nd	1.7±0.0	8.4	913±8

[a]nd means not detected. The detection limit is 2 mg/dm^3.

Table 3 shows the biochemical and physicochemical characteristics of the (inlet) influent and (outlet) effluent of the polishing plant installed at the mill. The results for BOD, SS, AN and colour are reported as mean value±standard deviation (n = 2). The grab and composite samples were treated as replicates and the mean values were determined from both. BOD of the influent and effluent, except for the eight day, ranged from 33.4±3.0 to 50.5±1.4 mg O_2/dm^3 and 2.3±0.0 to 8.3±0.6 mg O_2/dm^3, respectively. SS of the influent and effluent ranged from 20±7 to 60±2 mg/dm^3 and maximum 7 mg/dm^3, respectively. The OG contents were less than 4 mg/dm^3 for both the influent and effluent. AN of the influent and effluent ranged from 35.9±6.2 to 54.3±0.0 mg NH_3-N/dm^3 and 1.1±0.0 to 2.8±0.6 mg NH_3-N/dm^3, respectively. Colour of the influent and effluent ranged from 985±45 to 1178±8 ADMI and 690±10 to 913±8 ADMI, respectively.

3.2. ASSESSMENT ON THE QUALITY OF BOD AND SS AND COLOUR REDUCTION OF THE TREATED POME

Figure 3 shows the BOD of POME before and after the treatment in the polishing plant. With the exception of the 8th day of the trial, the average influent BOD is of 39.3±5.8 mg O_2/dm^3. These are much lower than the designed influent BOD of 200 mg O_2/dm^3 for the polishing plant. The BOD influent of the polishing plant is acceptably low due to the long HRT of the POME in the ponding system which is about 320 days, as shown in Table 1.

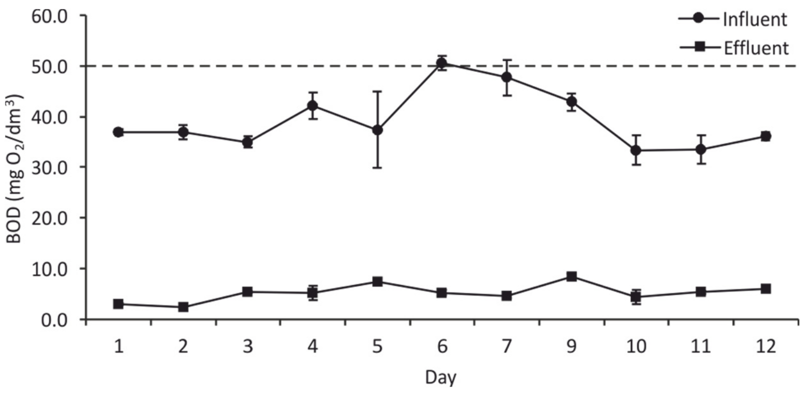

Fig. 3. BOD of POME after treatment in the polishing plant (mean values with error (SD) bars)

The theoretical design of the ponding system – when good managing practice of ponding system is applied – allows the HRT to be in the range of 55–85 days to achieve final effluent BOD lower than 100 mg O_2/dm^3 [11]. The optimum design for anaerobic, facultative and aerobic ponds are: the optimum HRT is 30–45, 15–20 and 0–20 days; the optimum depth is 5–7, 1–1.5 and 0.5–1.0 m, respectively [11]. Long HRT (more than 300 days) in the assessed mill allows sufficient time for the degradation of organic content in POME therefore reduces its BOD below 50 mg O_2/dm^3 after the last aerobic pond.

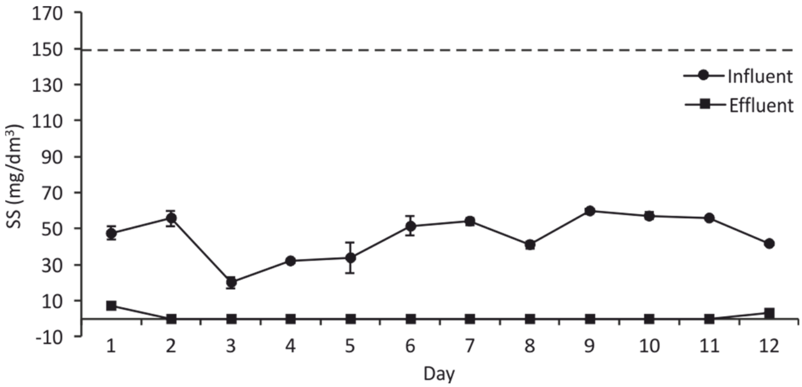

Fig. 4. Suspended solids content in the POME before and after treatment in the polishing plant

Figure 4 shows the content of SS in the POME before and after the treatment in the polishing plant. The SS of the POME was substantially eliminated. The influent SS ranged from 20±7 to 60±2 mg/dm^3 where it was almost not detected (less than 2 mg/dm^3) after being treated in the polishing plant. The influent of the polishing plant having SS average value of 43±10 mg/dm^3 is considered much lower compared to the allowed discharge limit of 150 mg/dm^3. This could be due to long POME HRT which allows long time for sedimentation of the solids in the ponds. The polishing plant can further reduce the SS in the POME due to filtration mechanism. Conventional system such as sequencing batch reactor (SBR) and activated sludge process relies on the sedimentation of solid which is time-consuming, and there is a risk of solid carry over into the clarifier overflow. Membrane system can forcibly prevent the solid from passing through due to the small pore size of the membrane surface. The drawback of the membrane system is that overload of the POME charging and SS can cause fouling of the membrane.

Besides long HRT of the ponding system, the installation of decanter unit to facilitate continuous removal of sludge also reduces the oil and solid in the POME. Accumulation of solid and other organic content carried over from the milling process into the POME treatment system could slow down the digestion of organic content during anaerobic and aerobic processed, which could possibly turn down the whole POME treatment process. This is usually observed through the formation of scum, which usually occurs as the bubbles rise to the surface, taking with them fine suspended solids [11]. Decanter unit installed at this mill continuously remove sludge and solids from the anaerobic ponds. The feeding flow rate of the POME is 20.5 m^3/h. The solid phase containing ca. 50% moisture is used as fertiliser. Water from the decanter is returned to the pond.

Palm oil mills could opt for the conventional desludging process which is usually carried out every 5 years or when the HRT is significantly reduced. The desludging process is the removal of solid by excavating one or two anaerobic ponds. The sludge is let to dry and utilised as fertilizer. The cost of desludging process is a one-off expense, but may not be possible where land is limited. Thus, installation of dewatering system such as decanter, belt-press and filter-press will be more effective but with a higher capital cost. The solid recovered from the dewatering system is a potent fertilizer for plants [22].

BOD parameter has been used to regulate the treated effluent discharged from palm oil mills in Malaysia since 1978. The environmental regulation body in Malaysia, namely the Department of Environment (DOE), recently proposed a new regulation for palm oil mills in Malaysia. Besides the reduction of BOD limit from 100 mg O_2/dm^3 to 50 and 20 mg O_2/dm^3, colour parameter measured as the ADMI unit was also introduced as a new regulated parameter [7]. The proposed colour limit for the discharged treated effluent is 100 ADMI [7].

Table 3 shows that the colour of influent and effluent ranged from 985±45 to 1178±8 ADMI and from 690±10 to 913±8 ADMI, respectively. Table 4 shows the percentage of reduction of colour, BOD, SS and AN of the POME. The colour of the POME was reduced by 11–30% after being treated in the polishing plant. It shows that the colour was the least reduced compared to the reduction of BOD, SS and AN with an average reduction of 22, 85, 98 and 96%, respectively. While the reduction of discharge effluent BOD limit benefits the environment due to less organic load to the watercourse, there is no clear justification to introduce colour as a regulated parameter. The POME is a non-toxic liquid waste containing high BOD and COD values that can deplete dissolved oxygen in water bodies if discharged untreated. Therefore, monitoring of biochemical and physicochemical characteristics, namely the BOD, COD, SS, OG, and AN is more reliable and sufficient to prevent pollution to the rivers.

Table 4

Reduction of BOD, SS, AN and colour for the treated effluent [%]

Parameter	Day											
	1	2	3	4	5	6	7	8	9	10	11	12
BOD	92	94	85	88	80	90	91	46	81	87	84	83
SS	85	~100	~100	~100	~100	~100	~100	~100	~100	~100	~100	93
AN	93	97	97	98	94	96	94	97	95	95	96	97
Colour	27	30	21	19	11	18	22	20	23	27	24	20

3.3. ASSESSMENT OF THE POLISHING PLANT OPERATION WITH RESPECT TO OTHER SYSTEMS

Table 5 shows the polishing plant monitoring activity during operation. The scope of monitoring was selected based on the standard operating procedure for the polishing plant provided by the mill. Dissolved oxygen (DO) at the bioreactor pond (Fig. 1) is the main parameter monitored during operation. Measuring of DO was conducted on an hourly basis, but the results presented in Table 5 shows the daily average of the DO recorded. Sufficient oxygen level in the water ensures continuous digestion of organic content by aerobic bacteria. Failing to provide oxygen will slowly turn the domination of aerobic bacteria to anaerobic bacteria, which is undesirable. The DO level in POME must be kept at above 2 mg O_2/dm^3. DO levels in the bioreactor pond, as a safeguard measure, was kept above 3 mg O_2/dm^3 which ranged from 2.98 to 4.95 mg O_2/dm^3 as shown in Table 5. The oxygen is supplied to the water through mechanical aeration. The mill installed a total of 4 surface aerators.

Table 5

Daily monitoring activity of the polishing plant

Day	DO at bioreactor pond [mg O_2/dm^3]	No. of aerator(s) operated	Amount of effluent discharge [m^3]	Effluent discharge rate[a] [m^3/h]	Clean water flushing[b] [m^3]	Weather
1	5.12	2	245	40.8 (6 h)	19	cloudy
2	4.95	2	286	40.9 (7 h)	18	raining
3	2.98	3	200	50.0 (4 h)	25	clear
4	5.82	2	322	46.0 (7 h)	18	cloudy
5	3.72	3	194	32.3 (6 h)	47	clear
6	4.05	3	251	35.9 (7 h)	52	
7	5.63	2	292	48.7 (6 h)	50	
8	4.77	2	168	42.0 (4 h)	19	
9	4.72	3	186	46.5 (4 h)	21	
10	6.15	2	121	40.3 (3 h)	23	
11	5.58	2	238	39.7 (6 h)	19	
12	5.32	2	n/a	n/a	n/a	

[a]Values in brackets are referred to effluent discharge duration. Total daily operation hours (including flushing and cleaning) shall be more than the effluent discharge duration.

[b]Chemical cleaning of membrane was conducted every 4–5 days but was not reported in the table (flushing with clean water was conducted daily).

Table 5 shows that the number of operated aerator increased when the DO fell to below 4 mg O_2/dm^3. At least two aerators were kept in operation during treatment to supply oxygen continuously. The operational practice introduced by the mill is considered sufficient to ensure the polishing plant in well-working condition. Similar operational condition for the treatment of industrial leachate from municipal solid waste was also reported by Coban et al. [23]. Aerobic treatment of leachate was employed through the intensive introduction of oxygen using 10 surface aerators in a 110 000 m^3 membrane reactor tank. This is followed by ultrafiltration and nanofiltration system to further reduce its COD and solids content [23]. Intensive aeration coupled with both ultrafiltration and nanofiltration for the treatment of leachate is necessary due to the highly polluted incoming leachate with maximum COD and solids content of 40 000 mg O_2/dm^3 and 1500 mg/dm^3, respectively [23]. It was also observed that the polishing plant discharged 42.1±6.1 m^3/h of the treated effluent, which is about 60% of the designed capacity (ca. 70 m^3/h). The amount of effluent treated and discharged is correlated to the total FFB processed in 2016 which is similarly low, about 42% of the actual capacity.

Stability problems and operational difficulties are often associated with membrane systems due to high tendency of membrane's pores to clog with solids thus severely fouling the membrane. As the cake layers formed on the membrane surface, differential pressure across the membrane gradually increased and consequently reduced the filtration efficiency (permeability rate). The assessed technology used a hollow-type membrane which has larger surface area compared to a flat-sheet membrane. Additionally, submerged membrane modules reduce pressure requirement compared to pressurised membrane. In the submerged configuration system, membranes are fully immersed in water where vacuum is applied to draw the filtrate through membranes. Compared to pressurised configuration, high pressure feed pump is required to overcome its back pressure during operation. In terms of operation, the following practices are important to ensure sustained operation; 1) continuous aeration of wastewater inside membrane modules using (air) blowers to shake off solids deposit on the outer membrane surface, 2) daily flushing of membrane with clean water, and 3) weekly cleaning of membrane with chemicals (acid-based solutions). Chemicals used for cleaning in this assessment were not disclosed due to company's secrecy on the formulation of the chemical solutions. However, various chemicals are proven able to restore the permeability of membrane to its original state such as sodium hydroxide, nitric acid, and sodium hypochlorite, with reported restoration efficiency of more than 90% [24, 25]. Generally, diluted chemical solutions containing 0.1–2.0% acids are sufficient to clean the membrane. In many cases, it was shown that frequent cleaning and flushing is vital for membrane systems to avoid membrane fouling, which has been well demonstrated by the assessed system.

Performance of various POME treatment systems were also reported by other researchers, but mostly conducted either in laboratory or at pilot-scale [15–19, 24–27]. Table 6 shows performance of various systems for the treatment of semi-treated POME ranging from activated sludge, SBR, ultrafiltration membrane and reverse osmosis (RO). The lowest BOD of the treated effluent reported by Zhang et al. [25] using hollow-fibre membrane is about 36 mg O_2/dm^3. However, further treatment of effluent using RO reduced the effluent BOD to nil (not detected) which helped to achieve their purpose of reclaiming water to be used in a boiler process [25]. In another study, treatment using RO could even produce treated effluent characteristics similar to that of drinking water [24]. However for the case of palm oil mills in Malaysia, recycling of water is not necessary as the mills are allowed to discharge treated effluent that complied with the standard set by the DOE.

Table 6

Performance of various systems for POME treatment

System	Working capacity	Inlet effluent characteristics [mg/dm^3]^{a,b,c}	Treated effluent characteristics [mg/dm^3]^{a,b,c,d}	Removal efficiency [%]	Ref.
Activated sludge	34 dm^3	pH 7.8 BOD_5 1720 COD 3908 AN 319 OG 237	pH 7.0–8.0 BOD_5 120 COD 78 AN 58 OG 24	pH – BOD_5 93 COD 98 AN 82 OG 90	[15]
Sequencing batch reactor	1.8 dm^3 (1.36 cm^3/min)	COD 13 532 BOD 1,390 TSS 13,700	COD 1 854 BOD 178 TSS 1504	COD 86 BOD 87 TSS 89	[27]
Bioreactor + ultrafiltration (hollow PVDF membrane)	42.1 m^3/h	pH 8.0–8.5 BOD 39.3 SS 46 OG 4 AN 45.8 colour 1081	pH 8.4–8.7 BOD 5.2 SS 5 OG nd AN 2.0 colour 845	pH – BOD 87 SS 89 OG ca. 100 AN 96 colour 22	–
Ultrafiltration (ceramic membrane)	500 dm^3	turbidity 190 COD 11 460 BOD 4,570	turbidity 1.2 COD 7,835 BOD 1,752	turbidity 99 COD 32 BOD 62	[26]
Ultrafiltration (hollow fibre) + reverse osmosis	300 cm^3 (1.11 cm^3/min)	pH 9.08 turbidity 111 COD 775 BOD 42 AN 40.6 SS 290	pH (9.09) 9.48 turbidity (0.79) 0.39 COD (701) nd BOD (36) nd AN (40.4) 8.9 SS (nm) nd	pH – turbidity 99.6 COD ca. 100 BOD ca. 100 AN 78 SS ca. 100	[25]

[a]All parameters are expressed in mg/dm^3 unit except for colour (ADMI), turbidity (NTU), and pH.
[b]BOD_5 means BOD five-day standard method.
[c]Values in brackets are referred to reduction of parameters after ultrafiltration.
[d]nm means not measured, nd means not detected.

It is also shown that ultrafiltration membranes are able to efficiently reduce the SS due to filtration mechanism of effluent through micro-size membrane pores. Although there is a high tendency for the cake layers to form (which leads to membrane fouling), it is not without viable solutions. Turbidity, which can be regarded as indirect measurement of SS, was very low about 1.2 NTU and 0.79 NTU when treated using hollow-fibre membrane and ceramic membrane, respectively [25, 26]. Conventional systems such as activated sludge and SBR have low tolerance towards SS compared to membrane filtrations. Chan et al. [27] reported reduction of total suspended solids (TSS) from 13 700 to 1504 mg/dm^3 using SBR. Vijayaraghavan et al. [15] did not report the reduction of SS as they mainly focused on the reduction of other parameters such as BOD, COD, AN, and OG – which were significantly reduced from 1720, 3908, 319, and 237 to 120, 78, 58 and 24 mg O_2/dm^3, respectively.

Additionally, DO level was maintained at 1.8–2.2 mg O_2/dm^3, implying an important role played by supplied oxygen (air) to ensure degradation of organic matters through aerobic-biological activity in activated sludge process [15]. Chan et al. [27] also maintained the DO for SBR's system at 2–5 mg O_2/dm^3 for similar purpose. In current assessed system, DO was maintained at 3–6 mg O_2/dm^3 in the bioreactor as a pre-treatment of effluent prior to membrane filtration.

Membrane system is one of the most advanced treatment systems for treating POME, thus the (high) costly. The mill is imposed with the most stringent treated effluent BOD limit (20 mg O_2/dm^3) in the country; therefore compliance of the system towards regulation was carefully weighed against the cost. Actual price of various systems are not actually available in the literature, nor they are publicly displayed by the technology provider as the cost for fabrication, installation and commissioning varies with location, application and capacity. However, cost comparison between technologies as well as the specifications of systems can be depicted as shown in Table 7. High-end system such as RO is able to reclaim the treated effluent for other usage such as for boiler feed and mill process but comes with a high increased cost. Conventional process such as activated sludge and SBR can be used during early treatment of POME where removal of solids is not critical or for mills which are imposed with less-stringent regulation such as effluent BOD limit of more than 100 mg O_2/dm^3.

Table 7

Cost comparison and specifications of various systems

System	Solids tolerance	Energy requirement	Maintenance frequency	Footprint	Cost
Activated sludge	low	low	low	high	low
Sequencing batch reactor	low	low	low	high	low
Sand / stone filtration	medium	low	medium	medium	medium
Membrane filtration	high	medium	medium	medium	high
Reverse osmosis	very high	high	high	low	very high

4. CONCLUSION

The performance of the polishing plant consisted of a bioreactor and membrane filtration for the treatment of POME has been shown in this assessment. The performance was assessed based on the palm oil mill activity, ponding system and polishing plant. This assessment would help in understanding the role of milling process, ponding system, desludging activity and operation of polishing plant to achieve treated effluent BOD below 20 mg O_2/dm^3 consistently.

The assessed mill benefited from low palm fresh fruit bunch processed (42% of the mill's capacity) and large ponding system (up to 320 days hydraulic retention time) where the BOD was reduced from ca. 25 000 to 50 mg O_2/dm^3. The polishing plant further treat the POME until its BOD is less than 10 mg O_2/dm^3. However, it is admitted that the polishing plant is yet to perform its best due to low BOD loading, which is 50 mg O_2/dm^3 compared to the designed BOD load of 200 mg O_2/dm^3. It is recommended that further study be carried out during peak crop season where mill operates at higher throughput.

BOD of 20 mg O_2/dm^3 is by far the known lowest limit of regulation implemented in developing countries [28]. While appreciating the availability of technology to achieve BOD below 20 mg O_2/dm^3, implementation of 50 mg O_2/dm^3 should be considered instead for palm oil mills due to them being remotely located from water source for people. Exception is for palm oil mills located in the area where people are depending on the river stream as main water source for daily usage.

Suspended solids, ammonia nitrogen, pH, oil and grease for the influent having BOD of 50 mg O_2/dm^3 are: 43.1 mg/dm^3, 43.5 mg NH_3-N/dm^3, 8.3 and 3.3 mg/dm^3, respectively. These passed the current standards set, i.e., 50 mg O_2/dm^3 (BOD), 150 mg/dm^3 (suspended solids), 5–9 (pH) and 50 mg NH_3-N/dm^3 (ammonia nitrogen). The reduction of colour is not very significant, with treated POME colour of 690–905 ADMI, way beyond the proposed limit of 100 ADMI. This indicates unreadiness of Malaysian palm oil industry to adapt with the colour parameter regulation.

Performance comparison between bioreactor coupled with ultrafiltration with other available systems such as activated sludge, SBR, ultrafiltration membrane (hollow-fibre and ceramic), and RO was thoroughly evaluated. It can be concluded that selection of systems for the treatment of POME is highly depending on mill's requirement, mill's capacity, and effluent characteristics.

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