Conventional Methods and Emerging Wastewater Polishing Technologies for Palm Oil Mill Effluent Treatment: A Review

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Abstract: The Malaysian palm oil industry is a major revenue earner and the country is ranked as one of the largest producers in the world. However, growth of the industry is synonymous with a massive production of agro-industrial wastewater. As an environmental protection and public health concern, the highly polluting palm oil mill effluent (POME) has become a major attention-grabber. Hence, the industry is targeting for POME pollution abatement in order to promote a greener image of palm oil and to achieve sustainability. At present, most palm oil mills have adopted the ponding system for treatment. Due to the successful POME pollution abatement experiences, Malaysia is currently planning to revise the effluent quality standards towards a more stringent discharge limits. Hence, the current trend of POME research focuses on developing tertiary treatment or polishing systems for better effluent management. Biotechnologically-advanced POME tertiary (polishing) technologies as well as other physicochemical methods are gaining much attention as these processes are the key players to push the industry towards the goal of environmental sustainability. There are still ongoing treatment technologies being researched and the

1 outcomes maybe available in a while. However, the research completed so far are compiled
2 herein and reported for the first time to acquire a better perspective and insight on the subject
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4 with a view of meeting the new standards. To this end, the most feasible technology could be
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6 the combination of advanced biological processes (bioreactor systems) with extended
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8 aeration, followed by solids separation prior to discharge. Chemical dosing is favoured only
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10 if effluent of higher quality is anticipated.
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17 **Keywords:** palm oil, palm oil mill effluent, polishing technologies, sustainability, tertiary
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24 1. INTRODUCTION

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26 The palm oil industry has been an important economic contributor for countries like
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28 Malaysia, Thailand, Indonesia, Colombia and other tropical developing regions. While
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30 impressive export and production figures are widely reported in almost all palm oil or POME
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32 treatment literature, it is not astonishing that a massive production of the effluent has turned
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34 out to be a main source of water pollution. In Malaysia, it is estimated that at least 60 million
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36 tonnes of POME was generated in the year 2009 alone (Ng et al., 2011). For each tonne of
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38 fresh fruit bunch (FFB) processed, large quantities of POME containing 29 – 33 kg of 30°C,
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40 3-days Biochemical Oxygen Demand (BOD₃) are discharged into the water bodies (Thanh et
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42 al., 1980).
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51 In Malaysia, a lot of efforts on research and development had made the industry dotted with
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53 significant successful pollution abatement history. Being the pioneer in targeting sustainable
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55 palm oil industry, Malaysia has gained valuable experiences in developing technologies for
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57 both upstream and downstream processing. In the year 2011, the palm oil processing mills
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attained 95.5% compliance to the effluent discharge limits (DOE, 2011). This achievement will continue to soar higher when further aim for the implementation of greater environmental management initiatives such as Cleaner Production (CP), biogas capture for Clean Development Mechanism (CDM) (PEMANDU, 2010; Ng et al., 2011), Roundtable for Sustainable Palm Oil (RSPO) (Basiron, 2007), and possibly towards zero discharge is made.

Previous reviews have been published emphasizing the current conventional POME treatment methods and state-of-the-art laboratory treatability studies. Some papers emphasize reusing the effluent and the industry's solid wastes to attempt resource recovery. As the current scenario in palm oil research focus on tertiary/polishing treatment of POME to progress towards the challenging 20 mg L⁻¹ BOD₃ discharge limit, this paper aims to concisely review and report the POME tertiary/polishing technologies which have not been compiled before so as to gain an insight for better effluent management.

1.1 The palm oil industry at a glance

Development of the oil palm sector is marked as an industrial success story. As the main plantation commodity in Malaysia, the total plantation area has expanded from a mere 400 hectares planted area (year 1920) to 54,000 hectares (year 1960); subsequently to 2,692,286 hectares (year 1996) and the most recent statistic at year 2011 reviewed is 5,000,109 hectares of oil palm planted area (DOE, 1999; MPOB, 2012). Travelling across the country, oil palm trees are seen nearly in every bit of unfilled land. According to a stature report by Basiron (2007), forest and oil palm recorded 61.82 and 13.20%, respectively for land coverage in Malaysia. From such a huge area of palm oil plantation, the country is capable of producing more than 92 million tonnes of FFB to be processed by palm oil mills which are spread across the nation (MPOB, 2012). Up to year 2011, Malaysia recorded a total of 426 palm oil

1 mills in operation (DOE, 2011; MPOB, 2012), with 250 mills operated in Peninsular
2 Malaysia and the remaining 176 mills in Sabah and Sarawak.
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7 Fig. 1 illustrates the distribution of the palm oil mills throughout the country. In the
8 Peninsular, Pahang state has the highest number of mills while Sabah state tops the country at
9 123 mills in operation. Despite having the highest number of palm oil processing mills, Sabah
10 state nevertheless is well-known for its biodiversity lushness. Major rivers in Sabah state like
11 the Kinabatangan River, the Segaliud River, the Muanad River, the Segama River, the Pang
12 Burong River, and the Kalumpang River are important to the local communities, tourism
13 activities, and are getting severe exertions on conservation. Hence, most environmental
14 concerns allied with the palm oil industry accentuates in the Sabah state, such as the
15 implementation of the $20 \text{ mg L}^{-1} \text{ BOD}_3$ discharge limit. Seeing the abundant number of palm
16 oil processing mills in Malaysia, 30 additional mills are indeed under planning and
17 construction throughout the country while 3 existing mills are not in operation (MPOB,
18 2012). With data on the amount of FFB processed by mills, the quantity of POME production
19 can be projected. In Malaysia, the recorded national production rate for POME is 0.67 cubic
20 meters per tonne of FFB processed by mills (DOE, 1999; Ma, 1999; Ng et al., 2011). POME
21 can be further divided into the sterilizer condensate, clarification wastewater, and
22 hydrocyclone wastewater in a ratio of 9:15:1 (Wu et al., 2010). The information in Fig. 1
23 shows the booming Malaysian palm oil industry (year 2011), but in contrast, a large amount
24 of liquid wastes are produced requiring appropriate treatment before discharge.
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55 Fig. 1 – An overview of the Malaysian palm oil industry in year 2011. A – the number of
56 palm oil processing mills in operation; B – the fresh fruit bunches processed by mills
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(tonnes); C – the estimated POME production (tonnes); D – sterilizer condensate (tonnes); E – clarification wastewater (tonnes); F – hydrocyclone wastewater (tonnes).

1.2 Palm oil factory processes as sources of pollution

In Malaysia, the wet palm oil milling process is typically applied. The method uses hot water to leach out the oil, which also explains the large consumption of water resources for milling processes and the concomitant large production of wastewater. A less popular dry milling method uses mechanical presses on the digested mash to squeeze out the crude oil. In short, the crude palm oil extraction process starts with collection of the FFB from the oil palm plantations. In the palm oil processing mills, fresh bunches are delivered into horizontal sterilizers (commonly used in modern factories compared to the vertical sterilizers) or pressure vessels where a live steam is applied against the fruits at approximately 100-140°C for 25-30 minutes (small bunches, 3-6 kg) or 50-75 minutes (larger bunches, 17 kg) to cook the palm fruits. The reported pressure used in sterilizers was 35-45 psi. The primary objective of sterilizing the fresh bunches is to deactivate and henceforth inhibit the enzyme activity (lipolytic enzymes) of palm fruits. The fat-splitting or lypolitic enzymes can result in the breaking down of oil into free fatty acids (FFA). A rise in FFA could lead to low oil yield as the fat-splitting enzymes would hydrolyse much of the oil during the fruit pulping process. Other motives of sterilization include preparation of fruit pericarp for subsequent processing and pre-conditioning the nuts to lessen kernel breakage during both pressing and nut cracking. Moreover, sterilization helps to smoothen the latter process of mechanical stripping/threshing to free the palm fruits from the bunches. Mechanical stripping is facilitated when sufficient moist heat in the form of steam during sterilization can penetrate to the points of attachment between the fruits and bunches, hence allowing hydrolysis at these points. These sterilized fruits are then subsequently smashed to press out the crude palm oil.

1 The oil is further treated in purifiers and vacuum dried for storage and export (Ab Rahman et
2 al., 2011; Thanh et al., 1980; PORIM, 1985).
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10 Fig. 2 - Typical palm oil milling processes in addition to the sources of water pollution and
11 by-products generation from the processing of one tonne of FFB.
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17 In the process of crude palm oil extraction, huge quantities of water is required and is
18 typically obtained from the adjacent freshwater resources, i.e., the rivers, which incurs very
19 little treatment and pumping costs. A detailed palm oil milling process, describing the sources
20 and quantities of water and its subsequent wastewater generation, as well as the products and
21 by-products alongside the milling processes is presented in Fig. 2. The milling process
22 coupled with the information of water, wastewater, and by-products were results obtained
23 from a survey of seven local palm oil mills. The factories involved are located in different
24 locations around the Johore state, which are Kota Tinggi, Bukit Besar, Penggeli, Paloh,
25 Kahang, Segamat, and one factory in Seri Ulu Langat (Selangor state). To process 1 tonne
26 (1,000 kg) of FFB, about 1.50 cubic meters of water source are extracted mainly for the
27 operation of boilers and the hydrocyclone separator (DOE, 1999; Ma, 1999; Chavalparit et
28 al., 2006). In Malaysia, all palm oil mills have at least one boiler with steam generation
29 capacity varying between 15,000 to 30,000 lb per hour. Water-tube (WT) boilers and fire-
30 tube (FT) boilers are two common types used in local palm oil mills but the WT boilers are
31 favoured due to higher steam generation capacity (Rashid et al., 1998). The natural water is
32 treated and made suitable as boiler feed water to prevent corrosion of the boiler metal, scale
33 formation, foaming, and priming. In the WT boilers, the boiler feed water is evaporated into
34 steam under the influence by steam pressure, steam temperature, steam quality, and feed
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1 water temperature. At a process throughput level of 60 tonnes FFB per hour, about 410 to 455
2 kg tonne⁻¹ hour⁻¹ of steam is required (Cooper, 1983). The hydrocyclone separators on the
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4 other hand use the flow of water to separate two components of different densities by
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6 centrifugal force. Palm kernels have lower density compared to the palm shells. Using a large
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8 quantity of water, the equipment separates wet kernels for further processing in the kernel
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10 silo and wet shells. The wet shells, combining with other palm biomasses (dry shells and
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12 fibres) are used as boiler fuels for fuel and electricity generation for the milling processes
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14 (Ma et al., 1993). An alternative to the hydrocyclone separator is the more conventional clay
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16 bath separator which requires lower power consumption and capital costs (PORIM, 1985; Ab
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18 Rahman et al., 2011).
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27 In the milling processes, about 50% (0.75 cubic meters) of the water source eventually
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29 became POME while the other 50% turn out to be used water. The used water is discharged
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31 into the drains or rivers without going neither into the effluent stream nor the wastewater
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33 treatment system. The generation of POME is illustrated in Fig. 2 and the three main
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35 wastewater sources which combine to make up the POME is represented as Source 1
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37 (sterilizer condensate), Source 8 (clarification wastewater), and Source 10 (hydrocyclone
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39 wastewater). Typical characteristics of this type of wastewater is shown in Table 1 (DOE,
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41 1999; Khalid and Wan Mustafa, 1992; Ma et al., 1993; Rupani et al., 2010; Wu et al., 2010).
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(Table 1 goes approximately here.)

51 Table 1 – Characteristics of different sources of wastewater combining to produce the POME.
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56 The sterilizer condensate (or sterilizer waste), wastewater Source 1 in Fig. 2 resulted from the
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58 FFB sterilization process in a horizontal sterilizer or horizontal cylindrical autoclaves (DOE,
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1999). Steam at 3 bars is admitted to the sterilizer with the purpose of air removal and to rapidly raise the temperature of the FFB to the optimum value. In a single peak sterilization cycle, the minimum steam consumption is 190 kg hour⁻¹ tonne⁻¹ of FFB while the peak rate steam consumption is 500 kg hour⁻¹ tonne⁻¹ of FFB. For a multiple peak sterilization cycle, the minimum steam consumption is 240 kg hour⁻¹ tonne⁻¹ of FFB and the peak steam consumption will be the maximum that the steam system can support when pressure is being brought up after a blow-off (Whiting, 1983). Although these figures might vary among the palm oil mills due to the variation in type of sterilizers and the introduction of new technologies would have lowered the steam consumption rate, the report do deliver a guide to the consumption of steam by the palm oil mills. The sterilization process results in the production of a huge amount of condensate which must be removed speedily to avoid flooding of the bearings of the cage bogies as well as contamination of the sterilizer condensate with the hydrocarbon lubricant (Ab Rahman et al., 2011). The increasing level of condensate will have an effect on the contact between the fruits with the wastewater and oil will be washed out from the bunches in excessive quantities. For every tonne of FFB processed, approximately 0.27 cubic meters of sterilizer condensate is formed, or 36% of the total POME is made up of the sterilizer condensate (DOE, 1999; Wu et al., 2010).

The largest portion of wastewater contributing to the POME (about 60%) is the clarification wastewater (or separator sludge) discharged from the process operation of clarification of the extracted crude palm oil, denoted as wastewater Source 8 in Fig. 2. Pulp press is used to extract crude palm oil from the digested palm fruits. However, the crude oil produced at this point is a mixture of palm oil (35 – 45%), water (45 – 55%), and impurities consisting of either soluble or insoluble vegetable matter in varying proportions (DOE, 1999). Through the

1 mechanism of settling and centrifuging in a clarification tank, the clarified palm oil on top of
2 the tank is continuously skimmed-off and further purified in a vacuum dryer prior to sending
3 into the storage tanks. Meanwhile, the oily sludge settles at the bottom and it is delivered to a
4 sludge separator to recover the remaining oil (PORIM, 1985; Thanh et al., 1980). The left-
5 over would be the sludge waste which is discharged into an oil trap and further delivered in a
6 waste stream to the wastewater treatment system. It is reported that for every tonne of crude
7 palm oil produced, approximately 1.5 tonnes of sludge waste consisting of water and fibrous
8 debris is attained (Wu et al., 2010). In the context of FFB processed, about 0.45 cubic meters
9 of the clarification wastewater is produced for every tonne of FFB processed in the palm oil
10 mill. In comparison with another two wastewater sources which make up the POME, the
11 solids content in clarification wastewater is much higher due to the presence of a higher
12 proportion of both soluble and insoluble carbohydrate constituents in the wastewater (Ho et
13 al., 1984).

36 The third wastewater source (no. 10 in Fig. 2) is the hydrocyclone wastewater which makes
37 up around 4% of the POME (DOE, 1999; Wu et al., 2010). Residue (press cake) from the
38 press machine consists of a mixture of fibre and nuts. While the fibres will be separated and
39 sent to the boiler house, the remaining nuts are sent to the nut cracker and subsequently to the
40 hydrocyclone separator (Lam and Lee, 2011). The process separates the cracked mixture of
41 kernel and empty shell based on their differences in specific gravity. Employing a separation
42 medium of clay suspension or salt solution with a specific gravity of 1.12, the hydrocyclone
43 can effectively separate the kernels and the shells with specific gravity of 1.07 and 1.15 –
44 1.25 respectively (DOE, 1999; PORIM, 1985). The generation rate of hydrocyclone
45 wastewater is 0.03 cubic meters per tonne of FFB processed.

Other than the three main waste streams, there are minor sources of relatively clean wastewater which constitute the POME. Since the volume is unpredictable and the effect is inconsequential, these wastewater sources are often neglected and very seldom reported. The quantity of this wastewater depends on the palm oil mill operation. A survey of the palm oil mills identified 9 additional sources of wastewater generation, other than the typically reported sterilizer condensate, clarification wastewater, and hydrocyclone wastewater. They are presented in Fig. 2 as wastewater source 2, 3, 4, 5, 6, 7, 9, 11, and 12.

Wastewater Source 2 is generated as a result of floor washing in the digester and pulp press operation site. In the digester, soft and stripped palm fruits were mashed by the central rotating shaft carrying a number of mechanical arms. The high temperature rotating mechanism loosen the fruit's outer covering from nuts before delivering the homogenized oil mash to squeeze out the crude palm oil (Embrandiri et al., 2012; Lam and Lee, 2011). The produced crude palm oil with entrained impurities requires oil separation and purification. This is done in the oil room where clarification of the crude oil occurs. Floor washing in the oil room contributes to wastewater Source 3 (Embrandiri et al., 2012). Also in the oil room, the purification of crude oil produces a minor effluent which is denoted by wastewater Source 4. The purification process is mainly aimed to achieve a high degree of moisture removal (Chungsiriporn et al., 2006; Embrandiri et al., 2012; Prasertsan and Prasertsan, 1996). Vacuum drier further purifies the crude oil until it reaches moisture and dirt content below 0.1 and 0.01% respectively (DOE, 1999; Embrandiri et al., 2012). The occurrence of water overflowing from the vacuum dryer machineries contributes to wastewater Source 5.

Purification of crude oil in the horizontal or vertical clarification tank helps in maintaining oxidative stability besides preventing gums deposition (Igwe and Onyegbado, 2007). Besides the procedure of refinement of oil skimmed-off from the top of the clarification tank, the bottom phase processing contributes to some sources of wastewater. In the oil room, the bottom phase which is generally underflow sludge will go through oil recovery. Minor sources of effluent come from the strainer process (wastewater Source 6) and the desander process (wastewater Source 7). Strainer is a pre-treatment process for the underflow sludge whereby the solid bits are removed. The diluted crude oil or sludge is hence treated in desander for the purpose of sand removal prior to feeding into the high speed centrifuge to achieve oil recovery (PORIM, 1985).

Aside the oil room, there are several sources of wastewater generation as denoted by wastewater Sources 11 and 12. While large quantities of water are used in the form of hot steam, the steam turbine is an important section in the palm oil mill for steam (heat) generation as well as electricity as a by-product. Cooling the turbine generates a certain volume of wastewater to be treated in the wastewater treatment system (Chungsiriporn et al., 2006). The boiler too is found to contribute to some wastewater from the steam condensate and boiler blow down. Besides, there are also floor washing in the premise at locations where empty fruit bunches (EFB) are delivered for screw pressing. This is denoted as wastewater Source 9 in Fig. 2.

Due to various sources of wastewater, the resulting POME has fluctuating characteristics. The characterization of POME collected from different batches or days from different mills too will give different analytical results. Moreover, different oil extraction techniques, quality

1 of the palm fruits, the factory requirement on effluent discharge limit, climate as well as the
2 condition of the palm oil processing are thinkable reasons for the dissimilarity. Different
3 cropping season of the oil palm and mill activities have also affected the quantity and quality
4 of the POME produced (Wu et al., 2010).
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11 The waste streams from the hot water and steam usually delivers sterilized condensate, and
12 the clarification wastewater are typically segregated and collected in different oil pits for
13 residual oil recovery (Khalid and Wan Mustafa, 1992). The recovered sludge oil is poor in
14 quality and will not be included in the production of oil. Instead, these oils are drummed and
15 sold as technical oils for non-edible applications (Ma, 1991; 1999). After oil recovery, the
16 two waste streams mix together with the hydrocyclone wastewater to form a mixed
17 wastewater or the POME. In general, the POME when fresh is hot, acidic, thick and viscous
18 brownish or grey slurry. It has very high organic matter and is said to be 100 times as
19 polluting as the domestic sewage (Ma and Augustine Ong, 1985; Khalid and Wan Mustafa,
20 1992). POME is a colloidal mixture of water, oil, and fine suspended components. The
21 suspended components are mainly vegetative matters like cell walls, organelles, short fibres,
22 water-soluble carbohydrates ranging from hemicelluloses to simple sugars (glucose, reducing
23 sugars, and pectin), nitrogenous compounds (from proteins to amino acids), free organic
24 acids, lipids, as well as the assembly of minor organic and mineral constituents (Edewor,
25 1986; Foo and Hameed, 2010; Ma, 1991). Wu et al. (2009) further reported the presence of
26 Pentose, which is a building unit of insoluble carbohydrate. The suspended solids in POME
27 slurry are mainly cellulose matter mixed with small portions of residue oil. The effluent is
28 also reported to be non-toxic as the entire milling process does not use any chemical (Ma and
29 Augustine Ong, 1985; Khalid and Wan Mustafa, 1992; Igwe and Onyegbado 2007).
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Nonetheless, the remaining 50% or about 0.75 cubic meters of water used in the milling of palm oil are used water which does not combine in the POME effluent streams. Having quite a similar quantity with the POME, the used water could cause loss of water to the environment, either to the drains, adjacent rivers of the palm oil mills, or through evaporation. Piping leakages and wash waters used to flush the machineries are other sources of water loss to the environment. Indeed, a large portion of water are actually lost in the form of steam/vapour. Steam is a main form of energy used in the palm oil mills (Sommart and Pipatmanomai, 2011). Most processes rely on the consumption of steams and hot water during crude palm oil extraction. Steam lost through exhaust gases from the sterilizer was reported by Chavalparit et al. (2006) and DOE (1999).

With a large amount of water loss in the palm oil milling processes, several literature suggested ways to reduce water consumption and wastewater discharge from the factories. The palm oil industry can adopt source reduction, which is a highly desired effort and the highest rank in the federal hierarchy of integrated solid waste management (Tchobanoglous et al., 1993). In the context of water and wastewater, water conservation and minimization of effluent discharge are becoming highlighted issues, particularly in the palm oil industry. Among the driving forces to a better water management are the increasingly stringent environmental regulations, the palm oil industry's commitment to achieve sustainable palm oil, an intense scrutiny over the long-term health effects on human and nature, as well as the availability of clean water resources in the country is of paramount importance (Parthasarathy and Dunn, 2005). Reducing the quantity of POME can reduce the delivery of this wastewater to the treatment system to ease or lessen the cost of the ultimate treatment (Tchobanoglous et al., 2004). Several options available for water conservation and

wastewater reduction in the palm oil industry include milling process modifications, housekeeping practices, and utilization or recycling of the POME.

Most palm oil milling process modifications were found to accomplish maximum oil recovery or to recover as much oil as possible because the higher content of oil and grease characterised a higher strength of the wastewater (Schuchardt et al., 2007; Thanh et al., 1980). Thanh et al. (1980) reported a closed-system which can eliminate the release of effluent from the oil clarification room. A decanter as an extra unit between the vibrating screen and oil clarifier was used to separate the minor solid materials from the crude palm oil. The settled oil sludge are delivered to the three-phase nozzle centrifuge for oil recovery, the recovered oil are sent back to the clarifier, the sludge will have land application while the liquid phase are recycled back to press and oil clarifier to make up the dilution water. Thanh et al. (1980) also described the dry process where a wind silo is used to separate kernels from cracked shells by gravity. No water consumption is involved, but the variation of electricity voltage occurred in mills resulted in high kernel loss. On another hand, Schuchardt et al. (2007) suggested the application of a new sterilization process which does not generate condensate. The conventional autoclave sterilizer and a new oil recovery process can produce 0.45 cubic meters of POME per tonne of FFB processed while the new sterilizer process and new oil recovery process only produce 0.25 cubic meters of POME per tonne of FFB processed.

There are several in-plant control and housekeeping measures suggested by the Malaysian Department of Environment to optimize water use (DOE, 1999). Regular maintenance to avoid leaks in water pipelines and valves, skilled operation of the hydrocyclones to reduce

1 water usage, control of overflow in the press room and clarification room, as well as regular
2 equipment maintenance to prevent excessive wash-down are some of the cleaner production
3 measures described (Thanh et al., 1980). Installation of the trigger release valve on the end of
4 each hose is a cost effective approach in water-saving. Palm oil mill staff should be well-
5 informed about the importance of water conservation. Simple practices like shutting off
6 valves, water taps, and water hoses immediately after use in addition to ceasing of flushing
7 out spillages of oil and remnants into drains can avoid the profligacy of water (Thanh et al.,
8 1980). Other approaches of cleaner production include control of oil clarification
9 temperature, proper design and operation of oil traps, separation of effluent and storm water
10 drainage systems, as well as proper interim storage of solid waste materials (DOE, 1999;
11 Thanh et al., 1980). In Malaysia, the national average POME generation rate from palm oil
12 mills are 0.67 to 0.75 cubic meters per tonne of FFB processed (Ma, 1999; Ng et al., 2011). If
13 the factory is well-managed and good housekeeping practises are implemented, the amount
14 can be auxiliary reduced to only 0.5 cubic meters for the handling of one tonne of FFB (DOE,
15 1999). The national average for Thailand on the other hand is 0.60 to 0.89 cubic meters of
16 POME per tonne of FFB processed (Chavalparit et al., 2006; Chungsiriporn et al., 2006).

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43 Another option is to utilize or recycle the POME, where the effluent is seen as a cheap
44 renewable residue rather than a kind of wastes to be disposed (Salihu and Alam, 2012).
45 Indeed, it is a wasteful exercise to spend money to treat this high amount of POME followed
46 by releasing the effluent without further constructive applications. Treated effluent that is
47 good in quality can be directly used as feed water for boiler or hydrocyclone (DOE, 1999).
48 Turbines cooling water can be recirculated in-plant while the steam condensates can be
49 reused for the purpose of processing, cleaning, and washing (Thanh et al., 1980). A study
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1 which recycles the sterilizer condensate and cooling water to the processing unit has reduced
2 to 65% freshwater consumption and 67% wastewater generation. The clarification
3 wastewater too was channelled to the processing unit as mixing water, the decanter as
4 blending water, and to the separator as balancing water (Chungsiriporn et al., 2006). Besides,
5 partially-treated POME which contained substantial quantities of valuable nutrients is useful
6 for cropland application, particularly in fruits and vegetables' growth (Abdullah, 1992; DOE,
7 1999; Lim et al., 1991; Lim and Zaman, 1992; Salihu and Alam, 2012; Sulaiman et al.,
8 2011). Hence, use of the inorganic fertilizers of the oil palm plantations or other croplands
9 can be reduced. Schuchardt et al. (2007) also suggested the utilization of EFB and POME in a
10 combined-composting process which can fulfil the demand of sustainable palm oil
11 production. The process involved biological drying of the POME to produce much of
12 compost for agricultural applications.

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31 Other than the information on liquid POME, Fig. 2 also presented a mass balance for the
32 processing of 1,000 kg of palm fruits (Chan, 1999; DOE, 1999; Ma et al., 1993; PORIM,
33 1985). The steam sterilization process results in 900 kg of sterilized FFB whereby 100 kg
34 were lost as moisture and another 0.3 kg were oil in the condensate. The subsequent stripping
35 /threshing mechanism for fruit-stalk separation can produce 666 kg of fruitlets and 234 kg of
36 EFB. Indeed, the generation of EFB is represented as 23% of FFB processed in the palm oil
37 mills (Ma, 1991; Prasertsan and Prasertsan, 1996; Sridhar and AdeOluwa, 2009). The EFB
38 contained 152 kg of water, 82 kg of non-oily solids, and oil of less than 1 kg. Under high
39 pressure, the crude oil is extracted from the digested mash of fruitlets by use of the screw
40 presses. The crude oil slurry is fed to a clarification system whereby the mass balance denotes
41 further use of 173 kg of diluted water in the extraction of crude palm oil of 225 kg
42 (approximately 20% from FFB) (Sridhar and AdeOluwa, 2009). The bottom-phase or sludge
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1 waste is 180 kg. On the other hand, the press cake is conveyed to a depericarper whereby
2 press cake fibre of 180 kg and nuts are segregated. Press fibre cake generation is about 13.5%
3 of FFB processed and constitutes 74 kg water, 97 kg non-oily solids, and 9 kg oil (Ma, 1991;
4 Prasertsan and Prasertsan, 1996; Sridhar and AdeOluwa, 2009). Further processing of nuts
5 will produce total shell of 73 kg (water 15 kg, non-oily solids 57 kg, oil 1 kg) and total
6 kernels of 67 kg (water 14 kg, non-oily solids 19 kg, oil 34 kg). In terms of percentage of
7 waste generation in palm oil processing, shells and kernels are 5.5% and 6% of FFB
8 processed respectively (Ma, 1991; Prasertsan and Prasertsan, 1996; Sridhar and AdeOluwa,
9 2009). Finally, potash ash generation is reported to be 0.5% of FFB (DOE, 1999).

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24 (Figure 2 goes approximately here.)

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27 Fig. 2 - Typical palm oil milling processes in addition to the sources of water pollution and
28 by-products generation from processing of one tonne of FFB.

29 30 31 32 33 34 **1.3 Laws and legislations governing the industry**

35
36 In the 1970s, exponential growth of the palm oil industry resulted in severe environmental
37 problems. The Department of Environment (DOE) is hence liable for implementing and
38 enforcing environmental regulations against the industry. Among the regulations applied to
39 palm oil industries' waste management practices are:
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46 (1) Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations, 1977

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48 (2) Environmental Quality (Clean Air) Regulations, 1978

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50 (3) Environmental Quality (Scheduled Waste) Regulations, 2005
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1 Among the listed regulations, the Environmental Quality (Prescribed Premises) (Crude Palm
2 Oil) Regulations, 1977, is predominantly discussed. The regulations had specified detailed
3 provisions to be complied. Most attention is drawn to the limits for parameters of effluent to
4 be discharged into a watercourse or onto land. An increasingly stringent discharge limit into a
5 watercourse is shown in Table 2 as in the *Second Schedule*, under *Regulation 12(2)* and
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(Table 2 goes approximately here.)

Table 2 - Parameter limits for watercourse discharge.

To progress towards a cleaner environment, the DOE is planning to revise a more stringent
discharge limit to be imposed on effluent management. As stated in *Regulation 12(4)* – for
watercourse discharge and *13(6)* – for discharge onto land, the Director General can impose a
more stringent limit if it is necessary. Above and beyond, there is an attempt to impose 20 mg
L⁻¹ BOD₃ discharge limit on crude palm oil mill effluent. The scope of the discharge limit
covers environmentally sensitive areas such as tourism areas of East Malaysia (Sabah and
Sarawak States), and those locations in close proximity to water intake points. Since then, the
20 mg L⁻¹ discharge limit concerns have been circulating among the administrators, millers,
and researchers, as it is a challenge to be accomplished.

2. LIQUID WASTE TREATMENT

As the paper emphasizes POME tertiary/polishing treatment, typical or conventional effluent
treatment systems adopted by palm oil millers are briefly reported. Past review works on
POME treatment technologies are divided into categories such as aerobic digestion, anaerobic

1 digestion, and physicochemical methods. This paper departs from typical treatment methods
2 based on means of effluent discharge and hope to provide a different view for a better
3 appreciation and understanding of these well-established systems.
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10 **2.1 Discharge into inland watercourse**

11 Types of wastewater treatment options selected are based on the miller's preferences, the mill
12 location, and land availability to cater for the wastewater treatment plant (Ma, 1999). Out of
13 416 licensed prescribed premises, 267 mills have been given the permission to discharge their
14 liquid wastes into inland watercourse in the year 2009 (DOE, 2009). Normally, (1) the
15 ponding system as well as (2) the open tank digester and extended aeration system effluent
16 are discharged into inland watercourse. The criteria leading to the grant of licence for giving
17 permission includes (Legal Research Board, 2008):
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- 28 a) Whether it would be practical to adapt the existing equipment, control equipment or
29 industrial plant to conform to given conditions;
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- 34 b) The economic life of the existing equipment, control equipment or industrial plant, having
35 regard to the date of purchase;
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- 39 c) The quantity or degree of cut-back of emission, discharge or deposit of wastes to be
40 achieved;
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- 44 d) The estimated cost to be incurred by the licensee to comply to the given conditions; and
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- 47 e) The nature and size of the trade, process or industry being carried out in the premises.
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51 The specification of the characteristics of these wastes is as listed in Table 2 (Legal Research
52 Board, 2008).
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The ponding system is the most popular method adopted by more than 85% of palm oil mills (Ma, 1999). Ponding in general includes wastes stabilization lagoons (ponds) and oxidation ponds. Oxidation ponds on the other hand can be loosely categorized as aerobic, facultative, and maturation ponds, otherwise as facultative ponds when oxygen is deficient (Wong, 1980). The ponding system normally includes sand and oil traps, cooling ponds, acidification ponds, anaerobic ponds, facultative ponds, and aerobic ponds (in descending order). Manually operated sand and oil traps are pre-treatment unit operations. In cooling ponds, the raw POME is cooled down to lower than 35°C prior to feeding into subsequent ponds (Thanh et al., 1980). Aerobic ponds are usually constructed up to 1-1.5 m deep while the anaerobic ponds are usually 5-7 m deep, both in earth structure without lining. The organic loading rate differs from 0.2 – 0.35 kg BOD m⁻³ day⁻¹ (Ma, 1999). Anaerobic ponding can digest high amount of solids and is inexpensive, but requires long retention times and a huge land area, with solids accumulation frequently reported (Hojjat, 2009). Solids reaching 4.8 kg volatile solids m⁻³ day⁻¹ can be digested in anaerobic ponds (Khalid and Wan Mustafa, 1992). Retention time is 20 days in anaerobic ponds (Yacob et al., 2006a). In due course of operation, solid sludge will accumulate at the bottom of the pond where desludging/desilting is eventually required. In brief, the ponding system entails low maintenance, it is economical, it offers process and operational simplicity, and is a feasible means of treating high strength organic wastewater. However, a huge land area (1 ha to 5 ha) and long hydraulic retention times (HRT 40 to 200 days) are required (Thanh et al., 1980; Wong, 1980). In terms of dimension, a typical size of an anaerobic pond is 60.0 X 29.6 X 5.8 m (length x width x depth), taking a palm oil mill which has a processing capacity of 54 tons per hour as an example. Size of pond depends on the capacity of the palm oil mill as well as the area available for ponds (Yacob et al., 2006a). Solids accumulated may reach 31,500 mg L⁻¹ before ponding begins, but are removed during the process by suction pumps. After the

1 decanter-dryer and ponding treatment, about 130 mg L^{-1} could be reached at the final
2 discharge (Ma and Ong, 1985).
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7 Another common system applied is the conventional anaerobic-aerobic system (open tank
8 digestion and extended aeration) (Chan et al., 2010). The two-phased anaerobic digestion
9 consists of mild steel-made digesters which are open at the top and left unstirred. POME with
10 organic loading rates from $0.8\text{-}1.0 \text{ BOD m}^{-3} \text{ day}^{-1}$ undergoes approximately 20 days of HRT
11 in the anaerobic digesters. Open tank digesters are capable of removing chemical oxygen
12 demand (COD) by 81% (Yacob et al., 2006b). Subsequently, the effluent is further treated in
13 extended aeration ponds for additional reduction in COD and BOD. The HRT of the extended
14 aeration pond is 10 days (Ugoji, 1997). Mechanical surface aerators are used to supply air to
15 the treatment plant with HRT of about 40 days (Ma, 1999; Chan et al., 2010). Supernatant is
16 then discharged into a close by watercourse.
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34 **2.2 Land disposal**

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36 The second most favoured POME discharge manner is accounted for 96 licensed prescribed
37 premises that practiced land disposal (DOE, 2011). Supernatant from the (1) ponding system
38 (typically anaerobic ponds) or (2) treatment ponds in the decanter-drier system, (3) stirred-
39 tank digested POME, as well as (4) aerobic and (5) anaerobic digester bottom sludge are
40 sources of POME utilized for controlled land application techniques (Ma, 1991; Ma, 1999;
41 Zakaria et al., 2000). Through pond digestion processes, the nutrient content particularly
42 nitrogen and potassium will go down through leaching and settling of sludge solids at the
43 pond underneath. In contrast, tank digestion with agitation and stirring of effluent cause
44 negligible effects to nutrient content. This mechanism breaks down complex organic solids
45 for enhancing nutrient uptakes by plants (Zakaria et al., 1995).
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In general, closed tank digesters coupled with biogas recovery facilities are associated with land application (Ma, 1999). In comparison with open tank anaerobic digesters, closed tank anaerobic digesters are more efficient in removing COD (> 95%) at a lower HRT of 17 days (Yacob et al., 2006b). Closed systems also generate biogases which are eventually either converted to electricity in a biogas engine or burned into gas flare. In some cases, biogas can be used as fuel in modified diesel engines with induction motors to produce electricity (Puetpaiboon and Chotwattanasak, 2004). On the other hand, effluent from an open tank digester and extended aeration discussed in the preceding session are also discarded to land application, mainly for irrigation. The raw or partially treated POME is applied to land either by discharging to overland flow or applying directly for irrigation (Thanh et al., 1980). Commercial scales of land application systems have been highlighted (Zakaria et al., 1995; DOE, 1999; Lim et al., 1999) as below and their corresponding advantages and disadvantages are shown in Table 3:

- Sprinkler / pipe irrigation system,
- Furrow / gravity flow system,
- Tractor / tanker / pump system,
- Longbed system, and
- Flatbed system.

(Table 3 goes approximately here.)

Table 3: Advantages and Disadvantages of the various POME land application methods.

With regard to environmental concern, research has publicized that land application of POME at controlled loading rates has insignificant impact on soil and water resources

(Zakaria et al., 1995). Although POME is highly polluting, no toxicity is reported due to zero chemical addition throughout the wet milling process. POME nutrients and minerals could be accumulated by carrying out a stand-alone or off palm oil mills waste management strategy such as evaporation. The concentrated effluent is rich in plant nutrients, especially nitrogen (950 mg L⁻¹), phosphorous (150 mg L⁻¹) and potassium (1,960 mg L⁻¹) (DOE, 1999). It is therefore a good raw material for making fertilizer (Panda, 2013). Research also has revealed that no heavy metal accumulation has been detected in the soil, water and the crop in long-term POME receiving lands (DOE, 1999).

2.3 Composting

According to DOE (2011), 12 licensed prescribed premises in Malaysia were granted the permission to practice solitary composting. In most cases, anaerobic liquor from anaerobic ponds, and anaerobic sludge from open or closed anaerobic digested tanks are used for composting treatment at field scale. EFB are pressed and shredded upon collection for crude palm oil recovery. The pressed-shredded EFB are brownish in colour with a length size of 15-20 cm. EFB act as the main carbon source for the composting treatment due to its high cellulose and hemicelluloses content. By percentage of EFB, cellulose and hemicelluloses were 52.8 and 14.8%, respectively (Baharuddin et al., 2010); while the anaerobic POME sludge is a nutrient source reported for composting with high concentrations of nitrogen (3,600 mg L⁻¹), phosphorus (1,200 mg L⁻¹), potassium (2,400 mg L⁻¹), and magnesium (1,500 mg L⁻¹) (Ma, 1991).

The thickened anaerobic POME sludge from the bottom part of the clarifier tank is used for composting treatment. The total POME anaerobic sludge added into the EFB compost

1 throughout the process is about one tonne (1:1 ratio) (Baharuddin et al., 2010). A completed
2 composting process using shredded EFB and partially treated POME from an open anaerobic
3 pond takes 80 days with a final C/N ratio of 12.5. However, the characteristics of matured
4 compost are reported to show some discrepancy due to variation of partially treated POME
5 (Baharuddin et al., 2009). A more constant microbial seeding and nitrogen source from
6 closed tank anaerobic POME sludge is hence favoured with 40 days of composting period
7 and a final C/N ratio of 12.4 (Baharuddin et al., 2010). To cater for the concern on
8 groundwater and nearby freshwater resources pollution, several mills are facilitated with
9 leachate collection drains where run-over POME were channelled back to anaerobic ponds or
10 digester tanks for further treatment.
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26 **2.4 Other Methods**

27 Above and beyond the three key distinctive disposal approach as reported above, other mills'
28 practised subsequent disposal schemes (DOE, 2011):
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- 34 • Discharge into inland watercourse and land disposal (32 licensed prescribed premises)
- 35 • Discharge into inland watercourse and composting (3 licensed prescribed premises)
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43 These mills applied a combination of disposal methods. With such combination of the
44 disposal processes, it offers process flexibility and perhaps better control of each of the
45 treatment unit operations. Whatever treatment options are in operation, records of
46 enforcement have shown that the Malaysian palm oil industry is generally complying with
47 the prevailing national regulation of 100 mg L⁻¹ BOD₃ for inland watercourse disposal and
48 5,000 mg L⁻¹ BOD₃ for land disposal. Successful pollution abatement and emerging demand
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to fulfil the local requirement for better environmental protection has urged the DOE to further revise the national regulation to a more stringent BOD₃ discharge limit.

3. POME POLISHING / TERTIARY TREATMENT TECHNOLOGIES

As satisfying results are shown by the existing POME primary/secondary treatment technologies, POME polishing systems pull attention to further remove organic matters, total suspended solids, and colour reduction. Since the 20 mg L⁻¹ BOD₃ discharge limit came into enforcement, most polishing technologies are found incapable of performing consistently and continuously. The enforcement record is showing 95.5% compliance and in order to attain 100% compliance, the DOE discharge standard may need to be reviewed (DOE, 2011). Total suspended solids are frequently regarded as contributing to high BOD in the effluent. As such, attempts to filter out suspended solids through application of membrane separation technologies are rapidly made, optimistically to reduce BOD and suspended solids concomitantly in the final discharge. On the other hand, colour removal is attaining consideration as the final effluent is still in dark brownish colour. From an aesthetic point of view, colour treatment is receiving considerable attention particularly in tourism and environmentally sensitive areas.

Tables 4 and 5 present a synopsis of POME polishing/tertiary treatment technologies. Such attempt to gather the sporadic POME polishing/tertiary treatment research for the first time may nonetheless offer the palm oil industry an insight for better effluent management.

(Table 4 goes approximately here.)

Table 4 - Summary of technologies/systems in treatability studies for POME tertiary treatment/polishing.

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2 Treatability studies to polish POME accentuates on producing higher quality effluent while
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4 full scale polishing plants emphasize the discharge limit compliance. As most of the
5
6 technologies in treatability studies are more advanced and costly, they are seen to progress
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8 towards water reclamation and recycling. Membrane technology is frequently reported to
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10 produce a higher quality treated effluent capable of recycling boiler feed water and to even be
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12 reclaimed as drinking water. Nik Sulaiman and Chea (2004) applied ultrafiltration (UF) with
13
14 various membranes of molecular weight cut-off (MWCO) to polish biologically treated
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16 POME. The study suggested that membrane with higher MWCO produced higher fluxes but
17
18 lower MWCO produced better quality permeate. However, colour removal was ineffective
19
20 when applying membrane technology alone after the conventional ponding system. Findings
21
22 from a more recent study by Idris et al. (2010) suggested that pre-treatment of biologically-
23
24 treated POME before tertiary treatment using UF membrane resulted in better permeate
25
26 quality. Biologically-treated POME from ponding systems was subject to physical pre-
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28 treatment processes, namely coagulation and adsorption. Both processes were commonly
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30 applied to reduce SS from effluent. Permeate from UF membrane was found successful in
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32 COD, colour, and turbidity reduction.
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43 Besides applying membrane technology in biologically-treated POME, the technology was
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45 also attempted on raw effluent (Ahmad et al., 2003; 2006). Raw POME was subjected to
46
47 chemical and physical pre-treatment, consisting of coagulation (ferric chloride) and
48
49 flocculation aid (acrylamide), sedimentation, and adsorption using activated carbon. Effluent
50
51 was further treated using UF membrane and reverse osmosis (RO) membrane. The
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53 technology was successful in producing high quality effluent for water recycling. All reported
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55 cases above recommended that membrane technology is practical but only after it is
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1 integrated with pre-treatment processes. When more unit processes are included, the desired
2 effluent quality is reachable but the critical question will be the costs required. Palm oil
3 processing is a low cost activity and the applicability of a higher cost waste processing
4 system will be unconvincing to palm oil millers. Moreover, operations of membrane
5 technology often have fouling issues and flux reduction phenomenon. These problems can be
6 effectively overcome by using pre-treatment such as coagulation, adsorption, and pre-
7 oxidation. In addition, modest operation methods such as running modes, rinsing modes,
8 chemical cleaning, and air scouring can also achieve the desired goal (Goa et al., 2011).
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22 Another technology attempted for tertiary treatment of POME was advanced oxidation
23 processes (AOPs). The technology is basically chemical treatment using the highly reactive
24 hydroxyl radicals ($\text{OH}^\cdot$). A study conducted by Aris et al. (2008) applied Fenton oxidation to
25 polish biologically treated POME. Two processes used were ambient-Fenton and solar-
26 Fenton. The better performed solar-Fenton used oxidation mechanism and resulted in rapid
27 degradation of organic compounds in POME which subsequently lead to colour reduction in
28 the wastewater. Another study reported by Abdullah (2008) used the hydrogen peroxide
29 photolysis method. In short, solar-Fenton performed well in colour reduction compared to
30 COD whereas hydrogen peroxide photolysis performed better in COD reduction compared to
31 colour. Both studies were still at laboratory-scale and important operating conditions such as
32 reaction time, optimum pH and light intensity, dosage, as well as working volumes are
33 subjected for further detailed exploration. Nonetheless, the viable results on COD and colour
34 removal offered insights on the feasibility of AOPs as one of the POME polishing
35 technologies.
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Other than physical and chemical approaches, biological methods were also attempted to polish biologically-treated POME. POME from the conventional ponding systems had gone through activated sludge processes in anaerobic, anoxic, and aerobic conditions. Biological polishing systems applied more advanced biological processes such as bioreactor systems, attached growth systems, and granular sludge technologies. Zahrim et al. (2009) applied suspended activated sludge system in sequencing batch reactor (SBR) to polish anaerobically-treated POME. Colour removal was attained at about 0-14% while organic matter removal was at about 27-39% only. The study later applied an attached growth system where granular activated carbon was seeded with activated sludge in a SBR. The system was described to remove colour at about 28-41% while organic matter removal was at about 59-70%. High percentage of colour and COD removal in the latter system was reported due to the adsorption of colour compounds into the granular activated carbon while biofilm growth on the surface further oxidise the colour compounds. Biodegradation and adsorption mechanisms contributed 50% each in recalcitrant pollutant removal in this case. Chan et al. (2010) similarly applied SBR for the post-treatment of anaerobically-treated POME. The technology was positively applied (at laboratory scale) to accomplish significant COD, BOD, and SS removal due to the factors like high biomass acclimation during bioreactor start-up, high retention of mixed liquor volatile suspended solids (MLVSS), and good settleability of activated flocs.

In addition to independent biological processes, a more recent and popular technology to integrate biological and physical separation was frequently reported in POME tertiary treatment. For instance, Ahmad et al. (2009) evaluated a hybrid membrane bioreactor (MBR) system to sequentially treat raw POME in a series of activated sludge processes of anaerobic,

1 anoxic, and aerobic reactors followed by membrane separation in the aerobic zone. However,
2 the membrane system experienced fouling in long-term operation and membrane cleansing
3 did not restore the initial permeability. On the whole, the membrane technology is still
4 capable of treating POME significantly and produce a good quality effluent.
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14 Essentially, almost all kind of wastewater treatment technologies established have been
15 attempted to be applied in POME treatment and polishing treatability studies (either
16 laboratory or pilot-scales). Physicochemical and biological processes are performing
17 satisfactorily to manage POME. The key issues are still the applicability and practicality of
18 these technologies after considering several factors such as cost-effectiveness, operational
19 consistency, and system sustainability if operated as full-scale treatment plants in palm oil
20 mills in the future. Furthermore, POME's unique characteristic as organic, non-toxic, highly
21 coloured and existence of recalcitrant organic compounds in the wastewater are crucial
22 features to be considered in order to implement the full-scale technologies beyond lab-
23 developed researches. Extensive research is needed to narrow down the practicality gap
24 between treatability studies and full-scale treatment plants. Among some attention-grabbing
25 issues could be, but not limited-to, are scale-up studies, operational troubleshooting in full-
26 scale treatment plants, fundamental wastewater and technological researches to gain better
27 understanding of unit processes, process optimization, as well as operational flaws
28 identification.
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53 (Table 5 goes approximately here.)

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55 Table 5 – Summary of full scale technologies / systems for POME tertiary treatment /
56 polishing.
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2 Compared to treatability studies, full-scale treatment plants as listed in Table 5 are more
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4 matured tertiary treatment technologies ready for commercialization. While no previous
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6 reports or summaries of all the commercially available tertiary treatment technologies in
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8 Malaysia were found, information of the technologies reported in this paper were collectively
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10 taken from notes and presentations of seminars and workshops, as well as through verbal
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12 survey to the participated palm oil millers and sporadic internet resources. Also, these
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14 technologies reported are offered by the technology providers, no information and laboratory
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16 data are available however, on the system performance. The purpose of the assortment of
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18 polishing technologies here is to provide important and first-hand information on available
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20 options, typical processes used, and appreciation of these readily-available technologies as a
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22 way towards better management of the POME.
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34 The use of MBR has been reported by Sulong et al. (2007). The membrane installation is
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36 aimed to replace the secondary clarifier after biological treatment in anoxic and aerobic
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38 activated sludge processes. Among the benefits of membrane instead of clarifier are smaller
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40 footprint, the ability for high solids concentration retention, and producing effluent
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42 appropriate for reuse in the palm oil mills. The cost reported is about RM 2.3 million for a
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44 typical 40 tonnes FFB hr⁻¹ mill. Other MBR offer was reported by Moro (2010) where
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46 submerged membrane was installed in both anaerobic and aerobic tanks. Besides, a
47
48 biological-physicochemical treatment process technology was also announced by the MPOB
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50 (Sulong and Abdul Wahab, 2008). The combined and compact biological-chemical-physical
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52 treatment process offered SS, ammonia, and colour reduction through its odour-free treatment
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54 to produce treated effluent accomplished for water reuse. A small footprint plant (only 40%
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1 compared to conventional activated sludge processes) producing high quality and reusable
2 effluent is probable at the costs of about RM 1.4 million for a 30 tonnes FFB hr⁻¹ mill.
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9 The POME tertiary treatment (polishing) technology is expected to be consistent, sustainable,
10 and inexpensive. Most systems offered by the technology providers ranged in costs of
11 between RM 1.5 to 2.0 million. To cater to the criteria of sustainability, chemical addition or
12 processes which required high energy consumption are hence unfavourable. Resource
13 recovery of the palm oil milling by-products as well as water reclamation are usually
14 incorporated as a marketing strategy in the commercial polishing systems. The criteria of
15 providing a system with consistent performance is the remaining concern to address.
16 Enquiries made to the Malaysian Palm Oil Board (MPOB) were able to inform that several
17 technologies for technological transfer from pilot tests to actual palm oil mills installation are
18 still ongoing and will be published when completed.
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38 The POME is generally organic waste, where presence of recalcitrant organic compounds
39 makes the effluent obstinate to treat. Thus, most full-scale treatment technologies are actually
40 advanced biological processes or biological-based technology integrated with chemical or
41 physical treatments. For instance, an SBR-constructed wetland was introduced by Chong and
42 Tan (2010) to bring the BOD₃ of treated effluent below 20 mg L⁻¹ and as a potential system
43 for water recycling. Partially-treated effluent from anaerobic digestion with BOD:N:P ratio of
44 100:46:4.0 (20 days HRT) entered the SBRs. SBRs represented secondary treatment and the
45 process is similar in concept with activated sludge system. Treated effluent was reported to
46 contain approximately 27 mg L⁻¹ of BOD₃ and 213 mg L⁻¹ of SS. The effluent then entered an
47 aquatic processing unit containing cattails plant. The system was a form of constructed
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1 wetland using the sub-surface flow system as a final polishing stage. Final discharge was
2 recorded at 17 mg L⁻¹ BOD₃ and 60 mg L⁻¹ SS. A system of this kind is a full biological
3 treatment, where no chemical addition is required and power requirement only occurred for
4 aeration purposes in the SBRs. Other full biological systems are briefly described in Table 5
5 (Tin, 2010; Idris, 2010; Mohd Siran, 2010; Lu, 2010; Shahrudin, 2010).
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13 Besides full biological systems, Chong (2010) introduced a tertiary treatment system to be
14 incorporated with the conventional ponding system. The biological system was applied,
15 followed by chemical coagulation (400-700 mg L⁻¹), flocculation (4-7 mg L⁻¹), and physical
16 treatment (sedimentation). Also the addition of lactic acid bacteria, yeast and photosynthetic
17 bacteria during the biological phase is reported. The final stage was a multi-media filtration
18 treatment to reduce SS in the final effluent. Bacteria decomposed both organic and inorganic
19 materials in addition to reducing the organic matter to a soluble state, henceforth turning into
20 food sources for other microbes. Enzymes catalyst secreted by the microbes will break down
21 complex organic material into smaller substances. Further oxidation and purification
22 processes ensure a stabilized effluent suitable for final polishing in the subsequent chemical
23 and filtration treatment. Jurgensen (2010) also reported a combined biological-chemical
24 technology to treat POME. The working principle is laid on application of ozone technology
25 as pre-treatment to the submerged fixed-film bioreactor. Ozone is an important oxidizer used
26 to break down the hardly biodegradable organic matters in POME. Once the organic
27 compounds were oxidized, the left-over organic matter was readily biodegradable in the
28 bioreactor with an active biofilm surface area of about 300 m² m⁻³. The only technology
29 reported without any biological component was described by Barr (2010). The technology
30 comprised of 4 phases, namely coagulation, flocculation, separation, and discharge. An
31 important feature of the technology was in the control of the sludge settleability. With the
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1 addition of a specifically-tailored coagulant, agglomeration of the destabilized particles
2 occurred rapidly to form flocs. An efficient separation process holds the key to pollution
3 abatement, where sludge were seen settled at the bottom of the tank in a recorded time of
4 only 3 minutes. The technology was described to be able to contribute to the final treated
5 POME of 20 mg L⁻¹ BOD₃.
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12 In a glance, suspended and attached growths advanced biological processes are principally
13 employed in full-scale wastewater treatment plants due to the organic-based wastewater
14 characteristics. Attached growth systems are usually favoured because the system
15 demonstrates higher organic loading capabilities, hence increasing the potential for treating
16 high organic waste loads per unit volume. Higher density of bacterial population, better
17 tolerance to process upset, smaller footprint, less expensive, and quick start-up are other
18 advantageous features of the system in comparison with suspended growth processes
19 (Steiner, 2000). Membrane filtration processes give very clear colour effluent, and are usually
20 integrated for water reclamation and reuse. Moreover, physicochemical treatment approaches
21 are allied with colour removal and bio-solids / sludge reduction in the final effluent.
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41 Efforts for better environmental management of the Malaysian palm oil industry have been
42 consecutively executed over the decades. It is known that the ponding system used for POME
43 treatment is not sufficient, thus various researches have been conducted and almost all kinds
44 of technologies have been reported to treat POME. Surprisingly, the new BOD₃ 20 mg L⁻¹
45 discharge limit is so challenging to the industry inspite of all the technologies attempted. The
46 major research issue is to meet the 20 mg L⁻¹ BOD₃ discharge standard and this has been a
47 challenge with the amount of research reported on treatment of POME. Therefore, BOD, SS,
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1 and colour are still parameters to be removed and are issues before an attempt to reach zero
2 discharge is achieved.
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7 High or low processing of FFB seasons in a year produced different loadings of incoming
8 POME into the polishing plants. Incompetent operation and maintenance worsen the situation
9 where some technologies were unable to perform optimally. Sludge removal and subsequent
10 beneficial application of these biomasses should be granted more consideration. Colour
11 causing compounds in the wastewater are known. Whether applying specific microbial agent
12 can break down these organic compounds is a challenge. Apparently some plant constituents
13 such as carotene, phenolic compounds, polyphenols, tannin and lignin, or melanoidin are
14 sources of the colour in POME (Neoh et al., 2013; Oswal et al., 2002; Limkhuansuwan and
15 Chaiprasert, 2010). Another point in support of the argument is, it is noticed that most POME
16 research nowadays are referring to old information such as the milling process and
17 wastewater characteristics. As the industry progress vigorously over the years, many factors
18 should be investigated in order to get further insights of POME management. Introduction of
19 hybrid palm fruits and several other new species, improved milling processes due to
20 technological advances, as well as water resources used in palm oil mills (supplied by water
21 companies, self-treated, or recycled) could be clues to new evidence on the exploration and
22 innovation for a breakthrough in palm oil wastewater research.
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48 **4. CONCLUSIONS**

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51 Intensive and dynamic research on POME pollution abatement has paid off efficaciously, and
52 the Malaysian palm oil industry is leading the trend towards sustainable palm oil production.
53 As a roadmap to palm oil zero emissions, POME polishing should be accomplished either for
54 water reclamation, reuse, or absolute pollution abatement. Apart from the recognised
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1 problems such as not being cost-effective and system inconsistency, a polishing / tertiary
2 treatment technology which exhibits reliable, sustainable, and affordable features is most
3 awaited. The technology is expected to be able to comply with the new 20 mg L⁻¹ BOD₃
4 discharge limit. Unsatisfactory performance of the wastewater treatment plant is often due to
5 the lack of competent personnel or operators and influential factors like design, operations,
6 loading, influent, and weather. From current surveys, the combination of bioreactor systems
7 with extended aeration and solids separation seems practicable. However, more research
8 efforts are needed for the confirmation of its appropriateness. While we are working on
9 POME treatment via end-of-pipe processes, it is perhaps a good move to consider a cleaner
10 production, and ultimately zero emissions in the industry for promoting a greener image and
11 implementing green marketing on the country's largest revenue earner – the palm oil
12 industry.

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List of Figures

Fig. 1 – An overview of the Malaysian palm oil industry in year 2011. A – the number of palm oil processing mills in operation; B – the fresh fruit bunches processed by mills (tonnes); C – the estimated POME production (tonnes); D – sterilizer condensate (tonnes); E – clarification wastewater (tonnes); F – hydrocyclone wastewater (tonnes).

Fig. 2 - Typical palm oil milling processes in addition to the sources of water pollution and by-products generation from the processing of one tonne of FFB.

Fig. 1 – An overview of the Malaysian palm oil industry in year 2011. A – the number of palm oil processing mills in operation; B – the fresh fruit bunches processed by mills (tonnes); C – the estimated POME production (tonnes); D – sterilizer condensate (tonnes); E – clarification wastewater (tonnes); F – hydrocyclone wastewater (tonnes).

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Table 1 – Characteristics of different sources of wastewater combining to produce the POME.

Parameter	Sterilizer Condensate	Clarification Wastewater	Hydrocyclone Wastewater
pH	5.0	4.5	- ^b
Oil and Grease	4,000	7,000	300
Biochemical Oxygen Demand (BOD) ^a	23,000	29,000	5,000
Chemical Oxygen Demand (COD)	47,000	64,000	15,000
Suspended Solids	5,000	23,000	7,000
Dissolved Solids	34,000	22,000	100
Total Nitrogen	600	1,200	100
Ammoniacal-Nitrogen	20	40	- ^b

All units in mg L⁻¹ except pH.

^aSample incubated for 3 days at 30°C.

^bNo values were reported for the parameter.

Table 2 - Parameter limits for watercourse discharge.

<i>Parameters</i>	<i>Limits According to Periods of Discharge</i>					
	<i>1-7-1978- 30-</i>	<i>1-7-1979-30-</i>	<i>1-7-1980-30-</i>	<i>1-7-1981-30-</i>	<i>1-7-1982-31-</i>	<i>1-1-1984 and</i>
	<i>6-1979</i>	<i>6-1980</i>	<i>6-1981</i>	<i>6-1982</i>	<i>12-1983</i>	<i>thereafter</i>
Biochemical Oxygen Demand (BOD) 3 days, 30°C; mg L ⁻¹	5,000	2,000	1,000	500	250	100
Chemical Oxygen Demand (COD); mg L ⁻¹	10,000	4,000	2,000	1,000	- ^b	- ^b
Total Solids; mg L ⁻¹	4,000	2,500	2,000	1,500	- ^b	- ^b
Suspended Solids; mg L ⁻¹	1,200	800	600	400	400	400
Oil and Grease; mg L ⁻¹	150	100	75	50	50	50
Ammoniacal-Nitrogen; mg L ⁻¹	25	15	15	10	150 ^a	150 ^a
Total Nitrogen; mg L ⁻¹	200	100	75	50	300 ^a	200 ^a
pH	5.0-9.0	5.0-9.0	5.0-9.0	5.0-9.0	5.0-9.0	5.0-9.0
Temperature °C	45	45	45	45	45	45

^aValue of filtered sample.

^bNo values were reported for the parameter.

Table 3- Advantages and disadvantages of various types of land application of POME.

Types of Land Application	Advantages	Disadvantages
Sprinkler/pipe irrigation system	Can reach higher planes and undulating area	It often requires exceedingly long sections of drip line
	High energy, capital and maintenance costs	Large areas may require the installation of a water pump or additional piping to maintain enough pressure throughout the drip line system
	Suitable for large expanse of land	
	Suitable to all types of soil except heavy clay	
	Elimination of the channels for conveyance, therefore no conveyance loss	
Furrow/gravity flow system	Flow rate is dependent on the size of furrow and are typically dictated by siphons or bank cuts	The efficiency of furrow irrigation is generally <65%
	Most suited to clay soils where the potential for leaching is far less	It has a higher risk of human exposure and labour requirement
	Low energy use	It cannot be used on steep land

Tractor/tanker/pump system	It has a simple design	Requires more energy for operation of centrifugal pump mounted on tractor
	It has no moving parts	High investment cost is required
	Cathodic protection systems are an economic alternative to periodic repainting and the associated downtime for repair	Corrosion may occur inside the tanker
Flatbed system	This consists of series of shallow bunded-beds of about 15 centimeter depth	Cost for provision of drainage
	It is good for a flat terrain	Recirculation system is required for reuse of wastewater
	It can be used for soils that do not disperse easily A large supply of wastewater can be handled easily	
Longbed system	It is similar to flatbed except that each bed may be as much as 70 meters in length	Cost for provision of drainage

It is good for a flat terrain

Recirculation system is required for reuse of
wastewater

It can be used for soils that do not disperse
easily

Table 4 - Summary of technologies / systems in treatability studies for POME tertiary treatment / polishing.

Technologies / Systems	Description	Removal Efficiencies	Organic Loading Rates	Hydraulic Retention Times	References
Membrane Filtration Processes	Pre-treatment – chemical coagulation (Envifloc 40L, 0.05 v/v), flocculation (Envifloc 20S, 0.015 v/v), sedimentation, and adsorption; followed by membrane processes – ultrafiltration (UF) and reverse osmosis (RO)	AN 99%; BOD ₃ 99%; COD 99%; Colour 100%; Odour 100%; OG 100%; Turbidity 100%; Water recovery 78%.	N/A	N/A	Ahmad et al., 2003; Ahmad et al., 2006
Membrane Filtration Processes	Ultrafiltration membrane process with hollow fibre membrane configuration; made by polyethersulphone material	AN 62%; BOD ₅ 97%; COD 98%; SS 98%; TKN 54%; Turbidity 80%.	N/A	N/A	Nik Sulaiman and Chea, 2004
Advanced	Technology to produce	COD 7-61%; Colour	N/A	N/A	Abdullah, 2008

Oxidation Processes (AOPs)	Hydroxyl radicals (HO*) - Hydrogen Peroxide/UV (H ₂ O ₂ /UV)	7-61%.			
Advanced Oxidation Processes (AOPs)	Technology to produce Hydroxyl radicals (HO*) – Fenton oxidation process (1) Ambient Fenton – inside laboratory under ambient light (2) Solar Fenton – open space directly under sunlight	Ambient Fenton – COD 75%; Colour 92%. Solar Fenton – COD 82%; Colour 95%.	N/A	N/A	Aris et al., 2008
Hybrid Membrane Bioreactor System	Phase 1: anaerobic - activated sludge process; phase 2: anoxic - activated sludge process; phase 3: aerobic (submerged-membrane).	COD 94%; SS 98%; TN 83%; TOC 96%; TP 64%.	1.77 - 1.87 kg COD m ⁻³ d ⁻¹	22 hr	Ahmad et al., 2009
Sequencing	96 hr SBR operation (Fill 5	COD 27-39%; Colour	N/A	96 hr	Zahrim et al., 2009

Batch Reactor	min, React 95 hr, Settle 15	0%-14%.			
(SBR), with	min, Decant 10 min).				
Suspended					
Activated					
Sludge (SAS)					
Sequencing	96 hr SBR operation (Fill 5	COD 59-70%; Colour	N/A	96 hr	Zahrim et al., 2009
Batch Reactor	min, React 95 hr, Settle 15	28-41%.			
(SBR), with	min, Decant 10 min).				
Activated					
Sludge –					
Granular					
Activated					
Carbon					
(ASGAC)					
Sequencing	22 hr SBR operation (Fill,	BOD ₃ 97-98%; COD	1.8 - 4.2 kg	20 hr	Chan et al., 2010
Batch Reactor	React 20 hr, Settle 2 hr,	95-96%; SS 98-99%;	COD m ⁻³ d ⁻¹		

(SBR)	Decant).	SVI 65 mL g ⁻¹			
Membrane	Pre-treatment consists of	COD >93%; Colour	N/A	N/A	Idirs et al., 2010
Filtration	chemical coagulation and	>99%; Turbidity			
Processes	flocculants aid (FeCl ₃ and	>99%.			
	C ₃ H ₅ NO), adsorption, followed				
	by ultrafiltration membrane				
	process.				

Abbreviations: AN – Ammoniacal-Nitrogen; BOD₃ – Biochemical Oxygen Demand (3-days @ 30°C); BOD₅ – Biochemical Oxygen Demand (5-days @ 20°C); COD – Chemical Oxygen Demand; OG – Oil and Grease; SS – Suspended Solids; SVI – Sludge Volume Index; TKN – Total Kjeldahl Nitrogen; TN – Total Nitrogen; TOC – Total Organic Carbon; TP – Total Phosphorus.

Table 5 – Summary of full scale technologies / systems for POME tertiary treatment / polishing.

Technologies ^a	Description	Removal Efficiency	References
Membrane Bioreactor Technology (MBR)	Phase 1 – Anoxic sector (activated sludge process); phase 2 – aerobic sector (activated sludge process); and phase 3 – ultrafiltration membrane process.	BOD ₃ 99%; COD 98%; SS 99%.	Sulong et al., 2007
Biological-Physicochemical Treatment Processes	Phase 1 – biological treatment (aerobic suspended growth processes – activated sludge process); phase 2 – chemical treatment (chemical coagulation – flocculation); and phase 3 – physical treatment (screening and sedimentation).	Ammonia, BOD ₃ , colour, and residual SS removal.	Sulong and Abdul Wahab, 2008
Sequencing Batch Reactor (SBR) – Constructed Wetland System	Phase 1 – sequencing batch reactor process for extended aeration; and phase 2 – constructed wetland system with aquatic processing units (<i>Cat Tails plant</i>).	BOD ₃ < 20 mg L ⁻¹	Chong and Tan, 2010
Suspended Packing in Activated Sludge Aeration	Phase 1 – clarifier and hence gradual acclimatization of ultra-aerobic microbes in completely mixed	BOD ₃ < 20 mg L ⁻¹	Tin, 2010

Tank, with Complete Mixing	activated sludge reactor; phase 2 – extended aeration of suspended packing; phase 3 – clarifier; and phase 4 – post-treatment (physicochemical treatment).		
Extended Aeration, Coupled with Fixed Packing in Activated Sludge Aeration Tank	Phase 1 – extended aeration process followed by clarifier; phase 2 – placement of packing materials in support racks (activated sludge reactor); phase 3 – clarifier with returned activated sludge (RAS); and phase 4 – polymer dosing.	$BOD_3 < 20 \text{ mg L}^{-1}$	Idris, 2010
Biological-Physicochemical Treatment Processes	Phase 1 – activated sludge system (activated sludge reactor) with extended aeration process; phase 2 – chemical coagulation and flocculation; and phase 3 – filtration process.	BOD_3 96%; SS 20%.	Chong, 2010
Aerobic Suspended and Submerged Attached Growth Biological Treatment Processes	Phase 1 – extended aeration process in activated sludge system; phase 2 – clarifier; phase 3 – aerated submerged fixed bed reactor; and phase 4 – sand filtration process.	$BOD_3 < 20 \text{ mg L}^{-1}$	Mohd Siran, 2010

Aerobic Suspended and Attached Growth Biological Treatment Processes	Phase 1 – extended aeration process in activated sludge system; phase 2 – clarifier; phase 3 – fixed bed reactor; and phase 4 – clarifier and sand filtration process.	BOD ₃ 50-75%.	Lu, 2010
Combination of Ozone and Submerged Fixed Film Biological Process	Phase 1 – polymer / dissolved air floatation (polymer/DAF) process; phase 2 – ozone system; phase 3 – submerged fixed film biological reactor with bio-media; and phase 4 – sand and carbon filter.	BOD ₃ 90%; sludge removal 50%.	Jurgensen, 2010
Attached Growth - Roughing Filter Solid Contact (RFSC) Technology	Phase 1 – roughing filter tower; phase 2 – solid contact tank; and phase 3 – clarifier.	BOD ₃ < 20 mg L ⁻¹ ; organics 75%.	Shahrudin, 2010
Membrane Bioreactor Technology (MBR)	Phase 1 – anaerobic submerged MBR coupled with biogas recovery; and phase 2 – aerobic submerged MBR.	BOD ₃ 99% (approximate)	Moro, 2010
Physicochemical	Phase 1 – chemical coagulation; phase 2 –	BOD ₃ < 20 mg L ⁻¹	Barr, 2010

Treatment Processes flocculation; and phase 3 – floc particles separation.

^aSubstitution of commercial names to more general technology / system terms are done referring to Tchobanoglous et al., (2004).

Abbreviations: BOD₃ – Biochemical Oxygen Demand (3-days @ 30°C); COD – Chemical Oxygen Demand; SS – Suspended Solids.