

DECOLOURISATION OF PALM OIL MILL EFFLUENT (POME) TREATMENT TECHNOLOGIES: A REVIEW

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ABSTRACT

Since last decade, global demand for edible oil is growing resulting in a remarkable increase in the areas under oil crop cultivation. The Malaysian palm oil industry is one of the largest palm oil producers in the world. In processing palm oil, high volume of liquid waste known as palm oil mill effluent (POME) is generated. The increasing demands of crude palm oil has resulted in the enormous increase of the number of palm oil mills in Malaysia contributing to large amount of POME. Currently, treatment technologies of POME gain a lot of attention in order to meet the standard discharge limits. The colour of POME, which previously was not an issue, is recently being highlighted and it will be incorporated in the regulation soon. Thus, this article provides review on colourants in POME and its possible decolourisation treatments. The possible decolourisation technologies that will be highlighted in this article are adsorption, coagulation and flocculation, membrane technology, microbial treatment, photocatalysis, etc. including their potential in POME colour removal efficiency.

Keywords: palm oil, environmental regulation, wastewater treatment, colour removal.

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INTRODUCTION

Palm oil industry is the largest agricultural sector in Malaysia that contributes to the country economic prosperity. It has become the world's second largest - behind Indonesia - producer and exporter of palm oil and its products. Malaysia has tropical climate suitable for oil palm cultivation. In fact, the crude palm oil (CPO) production has risen from 1.3 million tonnes in 1975 to approximately 20 million tonnes in 2018 compared to 19.5 million tonnes in the previous year (MPOB, 2015; Ying, 2018). It was reported that the number of palm oil mills has increased massively from about 10 mills in 1960 to 451

operated mills in 2018 in order to meet the CPO demands both locally and internationally (MPOB, 2018). The wet palm oil milling process is a typical way to extract palm oil from fresh fruit bunches (FFB) which consumes large amount of water and steam. During the extraction process, about 1.5 m³ water per tonne FFB processed is required and half of that becomes palm oil mill effluent (POME) (Loh *et al.*, 2013). Even though the economy grows enormously in this industry, it also generates large amounts of waste in the form of POME (60%), empty fruit bunch (EFB) (23%), mesocarp fibre (12%) and palm kernel shell (PKS) (5%) for every tonne of FFB in the milling process (Azhari *et al.*, 2010; Loh, 2017). The disposal of large quantity of waste generated by the palm oil industry is a challenging task and often seen as a serious environmental issue.

POME is a highly polluting wastewater (Ahmad and Chan, 2009) and has characteristics of thick brownish viscous liquid with a distinct offensive colour and an unpleasant odour, high colloidal suspension and slurry. As the production of CPO increases, so does the quantity of POME, *e.g.* in 2008, 44 million tonnes of POME were generated and it has increased to about 64 million tonnes in 2014

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(Loh *et al.*, 2014). The value is expected to increase as the CPO production increase by year. POME is one of the most difficult wastes to be managed due to its large volumes generated at a time (Madaki and Seng, 2013). POME is generated from the sterilisation, hydrocyclone clarification and shell/kernel separation in the line of CPO production with steriliser condensate and separator sludge being the two major sources of POME contributing the high strength characteristic (Poh *et al.*, 2010). However, as no chemicals are added in the CPO extraction, the POME generated is non-toxic to the environment (Ma *et al.*, 1993).

Current conventional POME treatment method and emerging technologies have been given attention as evidenced by the large number of researches and reviews which have been published in order to

find approachable solutions for managing POME. This article aims to review concisely and report on decolourisation treatment technologies of POME as to gain an insight for better POME management.

PROCESS DESCRIPTION AND SOURCES OF POME

The wet palm oil milling process is typically a method that has been applied in most mills throughout Malaysia. Normally, steam and water are used to leach out the oil which contributes to huge consumption of water resources and also generation of wastewater in the palm oil mills. *Figure 1* illustrates the stages involved in CPO extraction and POME generation. The following

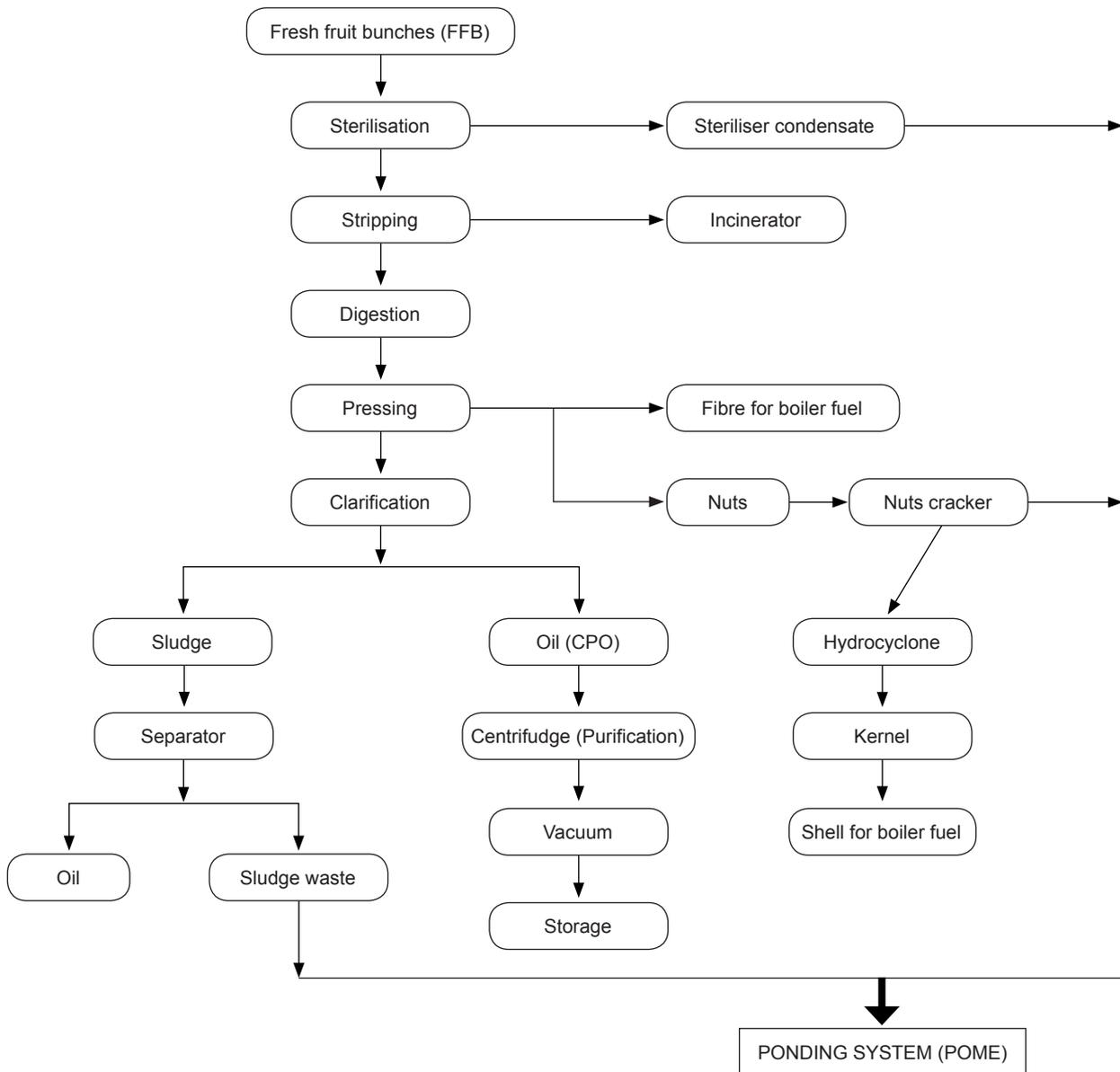


Figure 1. Flow diagram of crude palm oil (CPO) extraction and palm oil mill effluent (POME) generation.

section summarises some primary palm oil milling processes and sources of POME (Hassan *et al.*, 2006; Liew *et al.*, 2015; Rupani *et al.*, 2010; Wu *et al.*, 2010).

Sterilisation

The initial stage in extraction of CPO is sterilisation. Generally, sterilisation is a term referring to a process that eliminates all forms of microbial life (Block, 2001). During sterilisation, steam is injected directly to heat the FFB and to remove air as well. The purpose of this process is to remove external impurities, softening and loosening the fruits from FFB, detaching the kernels from the shells and deactivating the enzymes which are responsible for the build-up of free fatty acids by using hot water and pressurised steam. The presence of free acids in CPO is a concern because it leads to low production of oil since fat-splitting enzymes would hydrolyse much of the oil during the fruit pulping process. Build-up of free fatty acids during the process needs to be alerted so that maximum and good quality CPO can be produced. Steriliser condensate resulted from the steam consumption as shown in *Figure 1* is discharged to ponding system. It is about 36% of this stage contributes to POME (Poh and Chong, 2009). Increasing level of this condensate affects the quality of the fruits and the oil will be washed out from the bunches in large quantities. Approximately 0.9 t of condensate is generated for every tonne CPO processed (Wu *et al.*, 2010).

Stripping or Threshing

Upon completion of the sterilisation, the sterilised fruits are stripped and separated from the bunch stalk in a rotary drum thresher. At this stage, the fruits are elevated and dropped through the thresher in order to be knocked out of bunches.

The loose fruits are then transferred to the next process while the EFB can be recycled to the plantation as organic fertiliser or for mulching.

Digestion and Pressing

The loose fruits undergo digestion process in a heated cylindrical vessel equipped with stirrer and expeller arms. Mainly, this process digests and presses the fruits to loosen the mesocarp from the nuts. Hot water and steam are used to ease the oil extraction from the digested mesocarp. After that, the homogenous oil mash from the digester is moved forward through a screw press. The extracted oil is then purified and clarified in the next stage.

Oil Extraction, Clarification and Purification

Large amount of water is required during oil extraction process which is generally obtained from the freshwater resources, *i.e.* river. Homogenous oil mash is produced during the digestion process and is passed through a screw press followed by a hydrocyclone to remove water and fine solids. CPO is produced after the extracted oil is clarified and purified. Centrifuge and vacuum dryer are used to purify the oil before transferring it to a storage tank. At the same time, dirt and other impurities are removed from the oil. The CPO is subjected to high temperature in order to decrease its moisture content before sending to a storage tank. This step is essential to control the rate of oil deterioration during storage before its processing at a palm oil refinery. The by-product of clarification and purification process, *i.e.* the sludge, is the main source of POME in terms of pollution strength and quantity. About 1.5 t of sludge waste are generated per tonne of CPO produced. The properties of the sludge are shown in *Table 1*. Sludge from the separator is much more than in the other waste

TABLE 1. CHARACTERISTICS OF DIFFERENT SOURCES OF WASTEWATER FROM CRUDE PALM OIL PRODUCTION*

Parameters ^a	Steriliser condensate	Clarification wastewater	Hydrocyclone wastewater
pH	5.0	4.5	-
Oil and grease	4 000	7 000	300
Biochemical oxygen demand (BOD) ₅ ^b	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	-
Percentage composition (%)	36	60	4

Note: ^a All parameters are in units of mg litre⁻¹ except pH.

^b The sample for BOD analysis is incubated at 30°C for three days.

Source: *Liew *et al.* (2015).

streams which is the result of a higher proportion of carbohydrate constituents, both soluble and insoluble (Ho *et al.*, 1984). This could be the reason why biochemical oxygen demand (BOD) is very high in this waste stream.

Nut Cracking

During the pressing process to extract the oil, pressed cake comprising nuts and fibres are produced. Before being transferred to the nut/fibre separator, the pressed cake undergoes a preliminary breaking treatment to separate nuts and fibres by use of an air stream or by mechanical means. After that, the nuts are polished in order to remove any remaining fibres before passing to the nut cracking machine. The cracked mixture of shells and kernels is then separated based on their differences in specific gravity using upward suction (hydrocyclone) and a clay bath in a winnowing column. Any uncracked nuts must be removed and recycled. The washing water of the hydrocyclone is the third source of POME at approximately 0.1 t t^{-1} of CPO produced. It makes up around 4% of the POME. The properties of the hydrocyclone wastewater are shown in *Table 1*.

The main waste streams include steriliser condensate, clarification wastewater and hydrocyclone wastewater constitute the POME are presented in *Table 1*. The quantities of these main streams rely on the palm oil mill operation since its volume is unpredictable. Clarification wastewater contributes to about 60% of POME as compared to others due to large amount of water used during the oil extraction. The used water is then further delivered in a waste stream to the ponding system.

CHARACTERISTIC OF POME

Important Characteristic of POME

POME is generated mainly from the combination of separator sludge, hydrocyclone wastewater and steriliser condensate. *Table 1* shows that the separator sludge contains higher level of solid residues than the steriliser condensate and hydrocyclone wastewater. On average, 3.05 t of POME per tonne of CPO production is generated in the extraction process (Subramaniam *et al.*, 2008). Upon discharge from the mill, POME is a thick brownish colloidal mixture of water, oil and fine suspended solids (Wu *et al.*, 2010). The suspended solids in POME consist of oil residues, short palm fibre, cell walls, organelles, variety of carbohydrates ranging from cellulose to simple sugars, a range of nitrogenous compounds from proteins to amino acids, free organic acids and assembly of minor

organic and mineral constituents (Ugoji, 1997). Currently, ponding system is the most common treatment method for POME due to low operating and capital costs. However, this common method is becoming more unattractive due to the release of methane to the environment (Wu *et al.*, 2010).

POME contains residual oil that cannot be easily separated by conventional gravity-based systems. This has resulted in a high BOD of POME which is 100 times as polluting as domestic sewage. Thus, POME cannot be discharged without first being treated. BOD is normally used as an indication of the organic quality or the degree of organic pollution of water (Madaki and Seng, 2013). POME is also low in pH, which is about 4.5 due to the organic acids produced during the anaerobic digestion. As it contains organic acids in complex form, it is suitable to be used as carbon sources for microbial manipulation (Alias and Tan, 2005). The temperature of raw POME is approximately 80°C - 90°C due to the introduction of heat and vigorous mechanical processes during palm oil milling (Hassan *et al.*, 2006). POME is non-toxic since no chemicals are added to the extraction process (Khalid and Wan Mustafa, 1992).

Generally, the characteristic of POME varies widely and is dependent on the operation and quality control of individual mills; and also, activities such as closure of the mill and occasional public holidays (Hassan *et al.*, 2006; Yacob *et al.*, 2006). It also varies considerably for different batches, days and factories, relying on the processing techniques and the age or type of fruits (Ng *et al.*, 1987). *Table 2* showed the permissible limits of critical parameters for industrial effluent according to Environmental Quality (Industrial Effluents) Regulation 2009. The regulation specifies two standards for effluent discharge which are Standard A and Standard B. Standard A is for discharges into any inland waters within catchment area whereas Standard B is for discharges into any other inland water throughout Malaysia (DOE, 2010). Particulates which consist of plant cell debris and fragments are completely organic in nature as shown by the very low ash content (Ho *et al.*, 1984). Besides organic composition, POME is also rich in mineral content, particularly phosphorus ($180 \text{ mg litre}^{-1}$), potassium ($2270 \text{ mg litre}^{-1}$), magnesium ($615 \text{ mg litre}^{-1}$) and calcium ($440 \text{ mg litre}^{-1}$) (Hassan *et al.*, 2006; Badroldin, 2010). These minerals are vital nutrient elements for plant growth (Habib *et al.*, 1997).

Conventional Treatment of POME

Common method for treating POME is the open pond system which employs the open type lagoon treatment. Approximately 85% of POME treatment

TABLE 2. PARAMETERS LIMIT FOR INDUSTRIAL EFFLUENT*

Parameters	Unit	Standard	
		A	B
Biochemical oxygen demand (BOD ₅) ^a	mg litre ⁻¹	20	40
Chemical oxygen demand (COD)	mg litre ⁻¹	80	200
Suspended solids	mg litre ⁻¹	50	100
Oil and grease	mg litre ⁻¹	1.0	10
Ammoniacal-nitrogen	mg litre ⁻¹	10	20
pH	-	6.0-9.0	5.5-9.0
Temperature	°C	40	40
Colour	ADMI ^b	100	200

Note: ^aThe sample for BOD analysis is incubated at 20°C for five days.

^bAmerican Dye Manufacturers Institute.

Source: *DOE (2010).

TABLE 3. SUMMARY OF PONDING SYSTEM

Process	Function	Advantages	Limitation
Cooling	Cool down the POME to lower than 35°C	Low HRT	Has the strongest sourly smell
Acidification	Convert the organic components into volatile fatty acids (VFA) and depresses the pH of the system	Promote the growth of the acid formers. Short HRT	The contents are thick and a layer of solid is covering the top
Anaerobic	Digest high organic contents and generates biogas	Low capital investment and operational energy	Longer HRT. Extensive land area
Facultative	Allow heavy solids settle down at the bottom and lighter solids float at the surface	Stabilisation pond. Reliable process. Easy to operate	Lack of sludge removal capability. Land intensive
Aerobic	Decompose organic matter by bacteria in the presence of oxygen	More efficient and short HRT compared to anaerobic process	High operating cost

Note: POME - palm oil mill effluent; HRT - hydraulic retention time.

is based on conventional biological treatment methods of acidification, anaerobic, facultative and aerobic degradation (Loh *et al.*, 2013). Normally, ponding system includes sand and oil trap, cooling ponds, acidification ponds, anaerobic ponds, facultative ponds, and aerobic ponds (Liew *et al.*, 2015). According to Loh *et al.* (2013), the current ponding system in Kilang Kelapa Sawit Labu, Sime Darby in Negeri Sembilan, Malaysia, consists of a cooling pond, an acidification pond, two anaerobic ponds, two facultative ponds, and a final discharge pond. The overall hydraulic retention time (HRT) of this ponding system is more than 100 days based on the current processing capacity of the mill.

Acidification pond is a stage to promote the growth of acid producing bacteria and its associated enzymes in order to degrade organic material into fatty acids. This stage is a very rapid process with its HRT of only two days. Meanwhile, anaerobic pond allows high organic contents to be

digested by bacteria in the absence of oxygen (Liew *et al.*, 2015). It is characterised by long residence time which is more than 20 days. Facultative pond generally consists of a mix of anaerobic, aerobic and facultative bacteria, which can grow with or without oxygen. It is classified as primary clarifier of conventional biological treatment which allows heavy solids to settle down at the bottom and lighter solids float at the surface. Further treatment of POME consists of feeding it into aerobic pond where organic matters are decomposed into carbon dioxide, water and cell biomass by aerobic bacteria in the presence of oxygen. This treatment is more efficient and the HRT is shorter than that for anaerobic digestion. All these ponding systems are summarised in Table 3.

Even though the ponding system is a simple technology, low operating cost and easy to maintain, huge land area and long HRT are required. Besides, it showed relatively poor efficiency with a discharge

end having high residual chemical oxygen demand (COD) and BOD in the POME (Zhang *et al.*, 2008). Therefore, proper POME treatment is important not only to ensure a sustainable economic growth in the palm oil industry but also to protect the environment.

Colour Resistance

POME is a potential environmental pollutant requiring urgent attention due to its considerably 'stubborn' colour characteristic. It is seen as a brownish liquid waste and has high turbidity (Ahmad *et al.*, 2006). The discharge of coloured treated POME into a river, though less toxic, is often objected by the public on the visible colour appearance as a sign of pollution (Zahrim *et al.*, 2009). Although the conventional ponding system is upgraded with anaerobic system, anaerobically treated effluent (AnPOME) still consists of dark brown colour (Zahrim *et al.*, 2014). Reuse of AnPOME is one of the alternatives to reduce the impact to the environment, but its dark colour makes the AnPOME unattractive for reuse application (Ratpukdi, 2012). The effluent still remains as a clear brownish solution even after the tertiary treatment (Poh *et al.*, 2010).

The colour of the effluent is due to plant constituents such as lignin, tannin, humic and fulvic acid-like substances and phenolic compounds as well as repolymerisation of colouring compounds including anaerobic fermentation by-product, *e.g.* melanoidin (Zahrim *et al.*, 2014; 2009). The lignin content in POME is around 1700-7890 mg litre⁻¹ contributing to brownish colour of the POME (Poh *et al.*, 2010). It also contains *p*-hydroxy-phenyl, syringyl and guaiacyl units (Mohan and Karthikeyan, 1997). The POME colour is hard to remove because the lignin and its degraded products are chemically stable, resistant to biological degradation and are intractable to be separated by conventional method (Mohan and Karthikeyan, 1997). It is resistant to biological degradation because of the ligneous structures within an organic complex which have a tendency to shield the cellulose from enzymatic hydrolysis (Han *et al.*, 1975). Moreover, several phenolic compounds in POME are coloured consisting of gallic, protocatechuic, 4-hydroxybenzoic, 4-hydroxyphenylacetic, caffeic, syringic acids, *p*-coumaric and ferulic acids (Jamal *et al.*, 2011). Another factor contributing to colour in the POME is the suspended and dissolved particles in water. Dissolved particles comprise of dissolved organic matters such as humus, peat, or decaying plant matters which can produce a yellow or brown colour (Mohammed and Chong, 2014).

Discharging coloured effluent to water bodies imparts adverse effect on aquatic environment. It

inhibits the growth of the desirable aquatic biota necessary for self-purification (re-oxygenation) by filtering the penetration of sunlight, thus, resulting in less photosynthesis activity (Zahrim *et al.*, 2009). It also causes serious depletion of dissolved oxygen which endangers aquatic life as an important source of food and nutrients (Igwe *et al.*, 2010). Therefore, disposing highly coloured POME into a water body could not sustain aquatic life leading to the long-term impairment of the ecosystem.

Decolourisation Treatment of POME

Decolourisation treatments of POME gain a lot of attention since the colour of POME is very hard to be removed. Several technologies have been introduced providing new ideas and cost-effective solution to ensure sustainable palm oil mills operation. The summary of decolourisation technologies is presented in *Table 4*.

Physico-chemical Treatment

Physico-chemical POME treatment has received some attention due to the effectiveness and system applicability. It is useful in applications where it is desired to combine an effluent treatment with the recovery of solids. The suggested physico-chemical treatment processes for POME include adsorption and coagulation or flocculation.

Adsorption

Adsorption is considered to be one of the most effective and proven technologies having potential application in both water and wastewater treatment. It is a rapid process where a molecule collides with a surface and sticks (Masel, 1996). Adsorption performance depends on contact time, dosage of adsorbent, initial concentration and pH of POME. Mohammed (2013) carried out a comparative adsorption study among palm oil wastes, *i.e.* PKS and EFB on POME colour. The percentage of colour removal was almost 100% in 12 hr by activated PKS and EFB. Both PKS and EFB were activated by microwave and chemical. Similar study was carried out by Jalani *et al.* (2016) using PKS as adsorbent to remove POME colour. The difference was PKS was activated by steam and the maximum colour removal was 76% within 72 hr. Another study by Sia *et al.* (2017) also performed adsorption method to remove colour from POME using acid washed-coconut shell activated carbon. It was successfully used to remove the colour with percentage removal of 61% within 48 hr. Even though these adsorbents were effective in POME colour removal, the activation process was quite complicated and costly.

TABLE 4. SUMMARY OF TECHNOLOGIES FOR PALM OIL MILL EFFLUENT (POME) DECOLOURISATION

Technology	Description	Colour removal efficiency (%)	Advantages	Limitation	References
Electro persulphate oxidation	Current density: 45 mA cm ² Contact time: 45 min pH 4 Dosage: 0.892 g S ₂ O ₈ ²⁻	97.96	Good removal efficiency. No additional chemicals required for pH adjustment. Simple operation.	Cost intensive process. High electrical energy consumption.	Bashir <i>et al.</i> (2017)
Ultrafiltration membrane	Hydrophilic hollow fibre polyvinylidene fluoride (PVDF) ultrafiltration membrane incorporated with titanate nanotubes PVDF-TiNT 0.5% Duration: 240 min	58.9	Energy conservative. simple operation. Low cost purification method. Easily to scaled up.	Dissolved solids are hard to be separated. Fouling easily. High running cost.	Subramaniam <i>et al.</i> (2017)
Ultrafiltration membrane	PVDF ultrafiltration nanocomposite membrane embedded with coupled zinc-iron oxide (ZIO)	70	-	-	Tan <i>et al.</i> (2017)
Adsorption	Adsorbent: coconut shell activated carbon Adsorbent dosage: 5% (w/v) Contact time: 48 hr Mixing speed: 150 rpm	61	Simple process. Low adsorbent dosage. Abundantly material. Waste to treat another waste.	High cost of activation	Sia <i>et al.</i> (2017)
Adsorption	Adsorbent: palm kernel shell activated carbon Activation: steam activation Adsorbent dosage: 15% (w/v) Contact time: 72 hr Mixing speed: 160 rpm	76	Simple process. Abundantly material. Waste to treat another waste.	High cost of activation. Longer residence time.	Jalani <i>et al.</i> (2016)
Adsorption	Adsorbent: montmorillonite (natural clay) Dosage: 0.5% (w/v) Contact time: 90 min Concentration of POME: 25% pH 7 Mixing speed: 300 rpm	>95	Good removal efficiency. Simple operation. Short detention time. Low adsorbent dosage used.	Cost intensive regeneration process.	Said <i>et al.</i> (2016)
Electro-coagulation	Current density: 56 mA cm ² Contact time: 65 min pH: 4.5	75.4	Simple process. Short detention time.	High consumption of energy. High running cost.	Bashir <i>et al.</i> (2016)

TABLE 4. SUMMARY OF TECHNOLOGIES FOR PALM OIL MILL EFFLUENT (POME) DECOLOURISATION (continued)

Technology	Description	Colour removal efficiency (%)	Advantages	Limitation	References
Hybrid adsorption-coagulation	Adsorption Adsorbent: Fly ash Dosage: 30% (w/v) Coagulation Coagulant: mango pit Concentration of coagulant: 50 g litre ⁻¹ Volume of coagulant: 1.2 ml	97	Good removal efficiency. Economically attractive.	Cost intensive process.	Asadullah and Rathmasiri (2015)
Combination magnetic field and adsorption	Adsorbent: commercial activated carbon Dosage: 20% (w/v) Contact time: 6 hr	68.05	Low temperature requirement. No additional chemicals required.	Expensive material and process. Cost intensive regeneration process.	Mohammed <i>et al.</i> (2014)
Photocatalytic	Loading of TiO ₂	70	Low capital cost. Easily available.	Excessive photocatalyst slow down the photodegradation.	Tan <i>et al.</i> (2014)
Adsorption	Adsorbent: palm kernel shell (PKS) and empty fruit bunch (EFB) Activation: microwave and chemical activation	100 (PKS) 98 (EFB)	Good removal efficiency. Simple process. Waste to treat another waste.	High cost of activation.	Mohammed (2013)
Biosorption and biodegradation	Microorganism: <i>Aspergillus fumigatus</i>	71	Low cost treatment process.	Culture maintenance is cost intensive. Longer detention times.	Neoh <i>et al.</i> (2013)
Combination coagulation and vacuum ultraviolet-hydrogen peroxide	Coagulant: alum Coagulation prior to vacuum ultraviolet-hydrogen process	99.8	Good removal efficiency. Short detention time.	Cost intensive process.	Ratpukdi (2012)
Fenton oxidation	Ambient-Fenton and solar-Fenton	92.4 (Ambient-Fenton) 95.1 (Solar-Fenton)	Good removal efficiency. Easy process.	Expensive process.	Aris <i>et al.</i> (2008)

A study by Said *et al.* (2016) showed that natural clay (montmorillonite) was able to remove POME colour by more than 95% within 90 min with 5 g litre⁻¹ in initial concentration of POME of 25%. This study showed that the removal efficiency of montmorillonite for colour was due to the adsorption capacity and surface charge of montmorillonite. The montmorillonite was negatively charged that came from isomorphous substitution and neutralised the cations in the solution which finally deposited on adsorbent surface.

According to Igwe *et al.* (2010), boiler fly ash had potential in colour removal of POME. The adsorption isotherm of POME showed that Freundlich isotherm gave a better fit followed by Langmuir and then Dubinin-Radushkevich isotherm. This showed that the adsorption took place on a heterogeneous surface, rather than the homogenous surface (Mohammed, 2013). Similar result was obtained by Sia *et al.* (2017) who revealed that the POME colour adsorption mechanism was mainly due to heterogenous system and chemical sorption. The adsorption rate was affected more by the number of available adsorption sites on the adsorbent surface than the effect of POME solution concentration. Besides, study by Igwe *et al.* (2010) showed that the amount of colour adsorbed increased with the increasing dosage of the boiler fly ash. The increase of percentage of colour removal was due to the increased availability of surface area for adsorption (Mohammed and Chong, 2014). Similarly, smaller particle size of 425 µm adsorbed more compared to bigger particle size of 850 µm as larger contact area was achieved (Igwe *et al.*, 2010).

The pH is one of the important parameters for adsorption technology and it has a significant effect on colour removal. It is concerned with the surface charge and degree of ionisation (Said *et al.*, 2017). It was revealed by studies that the colour reduction from POME with high percentage removal mostly was in acidic condition (Jalani *et al.*, 2016; Asadullah and Rathnasiri, 2015; Mohammed, 2013). In acidic condition, more protons will be available to protonate the adsorbent surface thus, increase the electrostatic attraction between negatively charged anion compounds and positively charged adsorption sites, facilitating an increase in the colour reduction (Latif *et al.*, 2014). Study by Bello *et al.* (2013) stated that coloured organic compounds extracted from POME easily formed negatively charged ion in aqueous due to its structure contain functional group of an aromatic ring, carboxyl group, hydroxyl substituent ranging from simple phenolic molecules to highly polymerised compound. This could be the reason why the colour reduction was mostly performed in acidic condition because there was electrostatic attraction between

the negatively charged coloured compounds and positively charged adsorption sites.

A combined magnetic field and activated carbon adsorption process for colour, total suspended solids (TSS) and COD removal of POME treatment (Mohammed *et al.*, 2014) showed a better removal rate in the presence of magnetic effect. The exposure of activated carbon to a magnetic field could influence its magnetically sensitive particles compared to sorbate molecules, thus, enhancing the adsorption performance (Mohammed *et al.*, 2014). The use of magnetic field improved the orientation of the molecules of the adsorbate towards the activated carbon pores, hence, facilitating the adsorptive process, and resulting in a gain in the adsorption time (Brito *et al.*, 2012).

Coagulation and Flocculation

For many years, coagulation of coloured effluent has been used either as main or pre-treatment due to its low capital cost. It is classified into two main categories, *i.e.* metal coagulant and polymer (Yaser *et al.*, 2013). Coagulation destabilises the suspension and encourages the particles to flocculate and form larger aggregates (Wu *et al.*, 2010). Meanwhile, flocculation encourages the get together of the destabilised particles, where they stick and form larger aggregates (Bratby, 2006). According to Zahrim *et al.* (2014), lignin-tannin removal is enhanced by a polymer coagulant, *i.e.* calcium lactate-cationic polyacrylamide. Addition of polymer in coagulation and flocculation processes in a desired dosage improves the size of the destabilised flocs and consequently enhances the settling rate (Zahrim *et al.*, 2010). Synthetic non-ionic and cationic polymers are excellent in removal of lignin via coagulation and flocculation processes. These, together with natural polymers (chitosan) and chemical coagulant (alum), were found to exhibit different colour removal ability in the order of non-ionic polymer < cationic polymer < alum chemical coagulant < chitosan (Ganjidoust *et al.*, 1997).

A combined chemical coagulation and vacuum ultraviolet (UV)-hydrogen peroxide pre-treatment plays a significant role in the reduction of colour of POME (Ratpukdi, 2012). The resulting colour removal was up to 99.8% making POME almost colourless. Alum was used prior to vacuum UV-hydrogen peroxide process since alum encouraged the particles to flocculate and form aggregates leading to colour reduction. According to Kito *et al.* (1998), both UV and hydrogen peroxide can be used alone to facilitate the degradation of certain contaminants since hydrogen peroxide is capable of destroying some halogenated compounds and most non-halogenated compounds in aqueous solution

whereas UV light itself is capable in degradation of contaminants by initiating bond cleavage. Yet, there is a limitation on the range of contaminants UV can degrade; thus, the time for the degradation is slow. Besides, any hindrance of the UV transmission light to the sample can decrease the efficiency of the process. This makes operation cost higher as optimisation is required. Hence, the combined hydrogen peroxide and UV treatment may be an efficient process for bio remediation.

Currently, electro-coagulation has been focused on by researchers to upgrade coagulation and flocculation technology. Study by Bashir *et al.* (2016) showed that using electro-coagulation method is able to decolourise POME up to 75.4% after 65 min contact time by using current density of 56 mA cm⁻² at pH 4.5. This method proved that the reduction of POME colour takes a shorter time as compared to coagulation method and it is a simple method as well. However, this technology is high cost due to requirement of high energy to operate. Hybrid technology also had been applied in order to upgrade the current technology and improve the reduction of colour from POME as well such as combination of adsorption-coagulation method. Hybrid adsorption-coagulation method using natural coagulant, *i.e.* mango pit and palm oil boiler fly ash (POBFA) as adsorbent was studied by Asadullah and Rathnasiri (2015) in order to remove the colour and other impurities present in POME. It was reported that the percentage removal of colour from POME was 97%. A few advantages have been highlighted using this hybrid process which are cost-effective, environmental-friendly process and improving water quality.

Membrane Technology

Membrane technology was reported to be able to produce reusable water by recovering the colour of effluent. This method has the ability to concentrate, clarify and separate colour continuously from the effluent (Anjaneyulu *et al.*, 2005). For decolourisation, this technology is used to separate and remove colour pigments via molecular sieving mechanism (Nataraj *et al.*, 2009). Subramaniam *et al.* (2017) applied polyvinylidene fluoride (PVDF) nanocomposite ultrafiltration (UF) with hollow fibre membrane incorporated with titanate nanotubes (TNT) for decolourisation of aerobically-treated palm oil mill effluent (AT-POME). The novelty of UF membrane was fabricated by dry / wet phase inversion technique. TNT offered superior surface area and hydrophilicity. The enhancement of membrane hydrophilicity promoted and improved membrane water permeation. The UF membrane exhibited the most promising result with colour removal of 58.9% with 0.5% TNT

throughout a period of 240 min. Furthermore, this membrane showed very minimal signs of fouling and able to operate until five continuous cycles. Similar study was carried out by Tan *et al.* (2017) who applied the same type of UF membrane but the incorporation of metal oxide was different. In this study, PVDF UF membrane incorporated with coupled zinc-iron oxide (ZIO) nanoparticles and was fabricated via similar phase inversion process. It was found that POME colour was best removed by 70% due to the increase in ZIO loading which had drastically increased the membrane surface negativity resulting in repelling the negatively charged colour pigments that were present in the AT-POME and hence, contributed to greater colour reduction.

Generally, zinc oxide as nanoparticles was used to improve the membrane hydrophilicity resulting in low pressure operation and high permeation for AT-POME (Tan *et al.*, 2017). Membrane porosity and surface area, membrane surface charge and membrane wettability influenced the membrane performance in removal of colour from AT-POME. Even though this technology is a simple process and could conserve energy, it still promotes membrane fouling and requires high instalment cost including the fabrication.

Microbial Treatment

In microbial processing, microorganisms such as bacteria, fungus, and others are used in treating effluent for COD, BOD, TSS and colour removal. Neoh *et al.* (2013) studied the decolourisation of POME using cultures of *Aspergillus fumigates* under response surface methodology. The maximum colour removal of POME was 71% after five days. It showed that the subsequent increase in biomass increased the adsorption of colour as well as other compounds from POME. The biosorption and biodegradation processes involved was simple and economical since POME itself was used as a carbon source for the anticipated growth of the microbial cells in biosorption of colour (Neoh *et al.*, 2013). However, decolourisation of POME using microorganism is very time-intensive as compared to other treatment technologies such as adsorption, oxidation, coagulation and flocculation, *etc.*

In a separate study, Solemaninanadegani and Manshad (2014), the isolated bacteria, *i.e.* *Micrococcus* sp., *Bacillus* sp., *Pseudomonas* sp. and *Staphylococcus aureus* and fungi *i.e.* *Aspergillus niger*, *Aspergillus fumigates*, *Candida* sp., *Fusarium* sp., *Mucor* sp. and *Penicillium* sp. showed significant effects on biodegradation treatment of POME. Raw POME, autoclaved and non-autoclaved, were incubated for seven days and the activities of the microorganisms were observed at 12 hr interval.

The result of POME supernatant showed that the non-autoclaved sample degraded better than that of autoclaved one. This suggested that the indigenous microorganisms found in the POME were more effective than the introduced microorganisms. The colour of POME based on the American Dye Manufacturers Institute (ADMI) decreased with increasing number of treatment days for all the samples inoculated with multi-microorganisms as well as the control sample. There was fluctuation in the metabolites of microorganism system dedicated for biodegradation of POME. However, the result showed stability in final stage. Despite the inconsistency, this treatment showed positive tendency in POME colour reduction.

Others

The use of titanium oxides (TiO_2) in photocatalytic process can also remove colour from POME (Tan *et al.*, 2014). Different dosages of TiO_2 were used to evaluate the effect of catalyst loading towards the photodegradation efficiency of POME. The result showed that 10 wt% of TiO_2 was able to remove >70% of the colour pigment. However, the colour reduction only increased slightly when the catalyst loading increased from 5 wt% to 10 wt%, probably due to the agglomeration of nanoparticles in the POME suspension and the excessive photocatalyst used causing penetration of UV-irradiation difficult and consequently slowed down the photodegradation (Tan *et al.*, 2014). Similar method was reported by Cheng *et al.* (2017), who used tungsten oxides photocatalyst under UV-irradiation to remove colour from POME. It was found that the maximum percentage of POME colour removal was 98.28% at optimum reaction time of 16 hr. It was highlighted that the tungsten oxides photocatalyst is suitable for photocatalytic decolourisation of POME but not suitable for photocatalytic degradation. Nevertheless, photocatalytic process is still a major challenge since the mechanism is far more complex considering other factors such as type of catalyst, pH, illumination source and additives (Lekelefac *et al.*, 2015).

Aris *et al.* (2008) carried out a study on tertiary treatment of POME using Fenton oxidation to remove COD and colour. Two types of Fenton process were evaluated, *i.e.* ambient-Fenton (inside the laboratory under ambient light) and solar-Fenton (open space directly under the sunlight). The highest removal of colour under ambient-Fenton treatment was 92.4% and 95.1% for solar-Fenton treatment. It was shown that the efficiency of colour removal in POME was affected by ferrous ion and hydrogen peroxide dosages during the treatment, but the reaction may be inhibited after optimum dosages were used due to the scavenging effect

of radicals resulting in the formation of HO_2 . The optimum dosages of both the reagents were strongly dependent on the type and strength of the treated wastewater. It can be observed that when the iron dosage was fixed, increasing the hydrogen peroxide dosage from 902.5 mg litre⁻¹ to 1397.5 mg litre⁻¹ increased the colour removal from 70% to about 78%. Conversely, when the iron dosage increased to 384.7 mg litre⁻¹, increasing the hydrogen peroxide by the same magnitude did not increase the performance but indeed reduced the colour removal from >90% to about 78%. It can be concluded that solar-Fenton gave a better colour removal than ambient-Fenton (Aris *et al.*, 2008).

Study on oxidation technology had been upgraded to electro persulphate oxidation which was carried out by Bashir *et al.* (2017). It was a treatment with the combination effects of electro-oxidation, electro-coagulation and electro-floatation (Bashir *et al.*, 2017). This technology is considered as an effective process in organic degradation by using anodic adsorbed oxidants or electrochemically generated oxidants in the bulk solution to carry out direct and indirect oxidation simultaneously (Barrera-Díaz *et al.*, 2014). It was found that the colour of POME was removed by 97.96% with 45 mA cm⁻² of current density, 45 min of contact time, pH 4 and 0.892 g $\text{S}_2\text{O}_8^{2-}$. The experiment was conducted by using two aluminium plates as anode and cathode. According to the study, the percentage removal of colour increased with current density and contact time. However, the colour removal slowed down after certain time due to very slow mineralisation rate of the remaining organic complexes (Zhu *et al.*, 2014). In this study, electrical energy consumption was the main concern, however, it was found that a smaller amount of energy was consumed as compared to the energy consumed by conventional electro-coagulation process.

FUTURE PROSPECTS

Wastewater treatment technology is amongst the most vital component in a palm oil mill operation due to the large quantity of POME generated during CPO production. Although the first stage of the anaerobic treatment of POME is effective in degrading the BOD, it does not have the ability to decolourise the POME. This has led to urgency to further explore R&D to reach a solution that can offer POME discharge limit compliance.

Basically, almost all types of wastewater treatment technologies established have been attempted in POME decolourisation. Yet, none of the stand-alone treatment could decolourise POME satisfactorily. Currently, integrated system is widely studied by researchers as an alternative to stand-

alone treatment for better POME decolourisation. Combination of a few potential technologies on POME decolourisation is applicable and practical in the future after considering several factors such as cost effectiveness, operational consistency, and system sustainability if operated as full-scale treatment plants in palm oil mills. Integrated system gains much attention as this kind of approach is the key to ensure the palm oil industry moving towards the goal of environmental sustainability. One of the feasible technologies could possibly be a combined advanced biological process followed by solids separation prior to discharge.

The physical and chemical properties of POME are crucial that need to be considered in order to implement full-scale technologies. Gap between treatability studies and full-scale treatment plants needs to be narrowed down by extensive research. Other issues that need to be considered in POME decolourisation are scalability, operational troubleshooting in full-scale treatment plants, wastewater characterisation and technological researches for better understanding of unit processes, process optimisation and operational flaws identification.

CONCLUSION

The treated effluent from the anaerobic digestion of POME is always dark brownish due to recalcitrant nature of POME. Coloured POME is influenced by the presence of lignin and tannin substances which unfortunately is not publicly receptive and is always linked to the environmental pollution. Several possible decolourisation treatment methods are adsorption, coagulation and flocculation, biodegradation, biosorption, photodegradation and others. However, none of the stand-alone treatment could fully decolourise POME, and hence, integrated system is required. Coagulation and flocculation show more potential as pre-treatment step followed by adsorption process for colour removal. Other decolourisation treatment technologies are also possible but require more technologies integration dependent on the palm oil mill operation system, capacity of oil mill, the ultimate mode of discharge, the economics of the establishment and maintenance facilities.

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