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REMEDIATION OF PALM OIL MILL EFFLUENT (POME) USING SELECTED BIOLOGICAL TECHNIQUES: A MINI REVIEW

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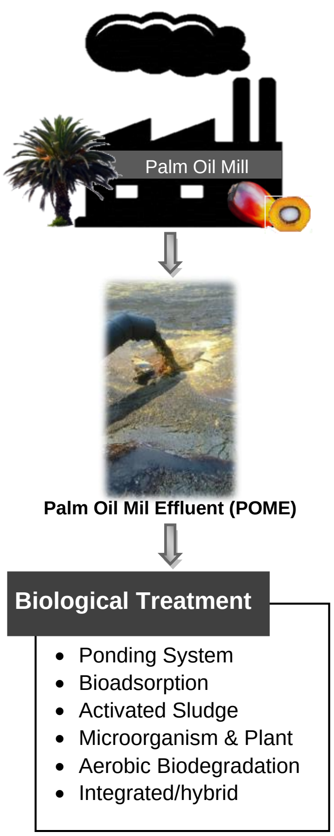
Graphical abstract



Abstract

Undoubtedly, industrial activities have produced a large amount of waste, which has significantly contributed to the global environmental problem. The palm oil sector, which is considered a water-intensive industry, is one of the industrial sectors that have become a major source of severe water pollution concerns. Normally, 50% of the freshwater used during the extraction of crude palm oil will end up in the production of undesirable liquid waste. Thus, proper regulation and enforcement are required to control the discharge of such waste to ensure the sustainability of water resource management. Based on research databases such as Scopus, ScienceDirect, Web of Science and PubMed the total number of publications focused on palm oil mill effluent (POME) treatment has increased significantly over the past five years. The increase in publications shows the growing concern about the POME issue among the scientific community. This mini review focuses on selected biological treatment techniques for remediation of POME focusing on ponding systems, bioadsorption, activated sludge, microorganism and plant, aerobic biodegradation and integrated/hybrid treatment strategies. The summary of optimum operating conditions, characteristics of the treatment system, properties of materials and performance of each treatment are discussed in detail. To achieve a high level of contaminant removal performance, it is critical to discover the synergistic effect between the treatment procedures, materials employed, operational cost, and circumstances.

Keywords: Oil palm, POME, wastewater treatment, biological treatment, optimum parameter

Abstrak

Tidak dinafikan, aktiviti perindustrian telah menghasilkan sejumlah besar sisa air buangan yang menyumbang kepada kemerosotan alam sekitar global. Sektor kelapa sawit, yang dianggap sebagai industri intensif air, merupakan salah satu sektor perindustrian yang menjadi punca utama kebimbangan pencemaran air yang serius Kebiasaannya, 50% daripada air mentah yang digunakan semasa proses perahan minyak sawit mentah akan berakhir kepada penghasilan sisa cecair yang tidak diingini. Oleh itu, peraturan dan penguatkuasaan yang sewajarnya adalah perlu bagi membendung pembuangan sisa tersebut bagi memastikan kelestarian pengurusan sumber air. Berdasarkan pangkalan data penyelidikan seperti Scopus, ScienceDirect, Web of Science dan PubMed, jumlah penerbitan yang tertumpu kepada rawatan efluen kilang kelapa sawit (POME) telah meningkat dengan ketara sejak lima tahun lalu. Peningkatan dalam penerbitan menunjukkan kebimbangan yang semakin meningkat terhadap isu POME dalam kalangan komuniti saintifik. Review ini memberi tumpuan kepada teknik rawatan biologi terpilih untuk pemulihan POME yang memfokuskan pada sistem kolam, biopenjerapan, enap cemar teraktif, mikroorganisma dan tumbuhan, biodegradasi aerobik dan strategi rawatan bersepadu/hibrid. Ringkasan keadaan operasi optimum, ciri sistem rawatan, sifat bahan dan prestasi setiap rawatan telah dibincangkan secara terperinci.Untuk mencapai tahap prestasi penyingkiran bahan cemar yang tinggi, adalah penting untuk mengetahui kesan sinergistik antara prosedur rawatan, bahan yang digunakan, kos operasi dan keadaan.

Kata kunci: Kelapa sawit, POME, rawatan air kumbahan, rawatan biologi, parameter optimum

1.0 INTRODUCTION

Historically, oil palm (*Elaeis guineensis*) trees are native to West Africa and are now grown in over 51 countries with a global production of 72,271,000 tonnes [1], where Indonesia, Malaysia and Thailand contributed 91% of global production of palm oil in 2020 [2]. Both Indonesia and Malaysia have become the focal points of the palm oil industry and cultivation, which contribute massively to each country's economic growth and also play a key component in rural development [3].

Generally, the oil from the outer mesocarp of palm fruit is dominantly high in palmitic and oleic acid content (about 50% saturated fat) which is very useful in biodiesel production, whereas palm kernel oil is high in lauric acid (more than 89% saturated fat) [4]. Thus, the feasibility of palm oil in the generation of biofuel and everyday products will significantly increase the demand for palm oil annually. In addition, oil palm can produce 3 to 8 times more oil than other plants such as olives, rapeseed, maize, coconut, and soy [5]. In fact, it was one of the most efficient producers of global oils and fats in 2018 with a total production of 70,875 million tonnes [6].

Wastewater generated from palm oil extraction is a significant source of environmental pollution which contains high total solids (40,500-72,058 mg/L), biological oxygen demand (25,000-65,714 mg/L), chemical oxygen demand (44,300-102,696 mg/L), oil and grease (145-9,341 mg/L), as well as producing a distinct offensive odour [7, 8]. Table 1 lists the effluent discharge limits for the oil palm industry in Malaysia, Indonesia, and Thailand. It is an undeniable fact that the disposal of untreated POME often leads to undesirable effects on the receiving ecosystems. The governments of each palm oil exporter country have set strict rules and regulations related to effluent discharge limits for the palm oil industry [9, 10, 11]. It is clear that the regulations on the limit discharge of effluent into watercourse are very important in order to protect the freshwater and coastal ecosystems. In 2021, the United Stated Department of Agriculture (USDA) [2] reported Indonesia, Malaysia and Thailand produced a total of 67,120 thousand metric tonnes of crude palm oil (CPO). The production of each tonne of CPO would generate around 0.5-0.75 tonnes of POME [12, 13] and, from our estimation, almost 41,950 thousand metric tonnes of POME would be generated by the three main palm oil producer countries in 2021.

Therefore, great efforts have been made by researchers, especially from palm oil exporter countries to overcome POME issues [14]. Awareness of environmental protection and sustainable development among the scientific community has developed progressively. Researchers are now focusing on developing alternative techniques for POME treatment at both laboratory and industry levels related to natural substances and eco-friendly materials or techniques [15, 16]. Therefore, the current manuscript aims to review biological treatment for treating the POME wastewater.

Other than biological treatment, various methods and strategies have been explored for improving POME treatment, such as coagulation/flocculation, electrocoagulation, membrane filtration and advanced oxidation processes [17]. However, this review will give some insight into current biological techniques such as bioadsorption, activated sludge, microorganisms and plants, and aerobic biodegradation to treat POME. In addition, the advancement of integrated or hybrid treatment strategies will also be discussed. This will provide valuable information to researchers and scientists to innovate advancement techniques for POME treatment.

Table 1 Effluent discharge limits for oil palm industry in Malaysia, Indonesia and Thailand

Parameters (units)	Discharge limits		
	Malaysia[9]	Indonesia[10]	Thailand[11]
BOD (mg/L)	100	250	100
COD (mg/L)	*	500	1000
Total solid (mg/L)	*	N/A	N/A
Suspended solid (mg/L)	400	300	150
Oil and grease (mg/L)	50	30	25
Ammoniacal nitrogen (mg/L)	150	20	N/A
Total nitrogen (mg/L)	200	N/A	50
pH	5 - 9	6 – 9	5 - 9
Temperature (°C)	45	N/A	40

Note: * No discharge standard after 1984, N/A not available.

2.0 BIOLOGICAL TREATMENT TECHNIQUES FOR POME

2.1 Ponding System

The conventional ponding system is the most commonly employed treatment method for POME. This is because the ponding system offers an affordable and easy technology with low operational maintenance and construction costs, so skilled workers are not required. Besides that, the ponding systems consume less energy due to the absence of mechanical mixing. In most cases, there is no operation management or monitoring, making the ponding system the most common option in the palm oil sector.

A ponding system involves four biological treatment processes, namely anaerobic, facultative, algae and aerated [18]. Figure 1 depicts the layout plan for the POME wastewater treatment plant [19]. Basically, the treatment processes can take place either in the presence of oxygen (aerobic) or in the absence of oxygen (anaerobic and facultative).

The biological treatment will remove the pollutant dissolved in wastewater which acts as nutrient for microorganisms. The organisms used may be bacteria, fungi, algae or plants as well as the enzyme system. For example, the conversions of pre-consumer solid waste such as vegetable and fruit dreg into garbage enzymes were investigated by Rasit and Kuan [20]. The pH of the garbage enzyme was found to be 3.65 at COD concentration about 121,636 mg/L which assign the highest content of organic content. POME treatment was performed with different concentration dilution of enzyme garbage and allowed to digest for 6 days. Test results of garbage enzyme showed a higher range reduction of TSS, COD and oil and grease (O&G) of almost 30-50%, 15-25% and 50-90%, respectively at 10% of enzyme garbage dilution concentration.

2.2 Bioadsorption

Bioadsorption process is a nature of surface phenomenon, in which the target pollutants adhere to the surface of the solid which has been considered as a simple, effective and low-cost technique for separating organic and inorganic contaminants in wastewater treatment. In addition, bioadsorption is a reversible process since the pollutant molecule can be removed from the surface of the adsorbent. This process is called desorption, whereby the adsorbent can be regenerated after the adsorption process [21, 22].

There are two general types of adsorbent, namely natural and synthetic adsorbents. Recently, a great deal of attention has been paid to natural materials adsorbents as alternatives to commercial adsorbents in POME remediation studies. Natural adsorbents offer several advantages including their availability in large-scale quantities, low-cost and have significant potential for physical or chemical modification [23].

The efficacy of agricultural and industrial solid wastes by-products has also been investigated for POME treatment. The application of waste-based materials as adsorbents for POME treatment can reduce the operational cost.

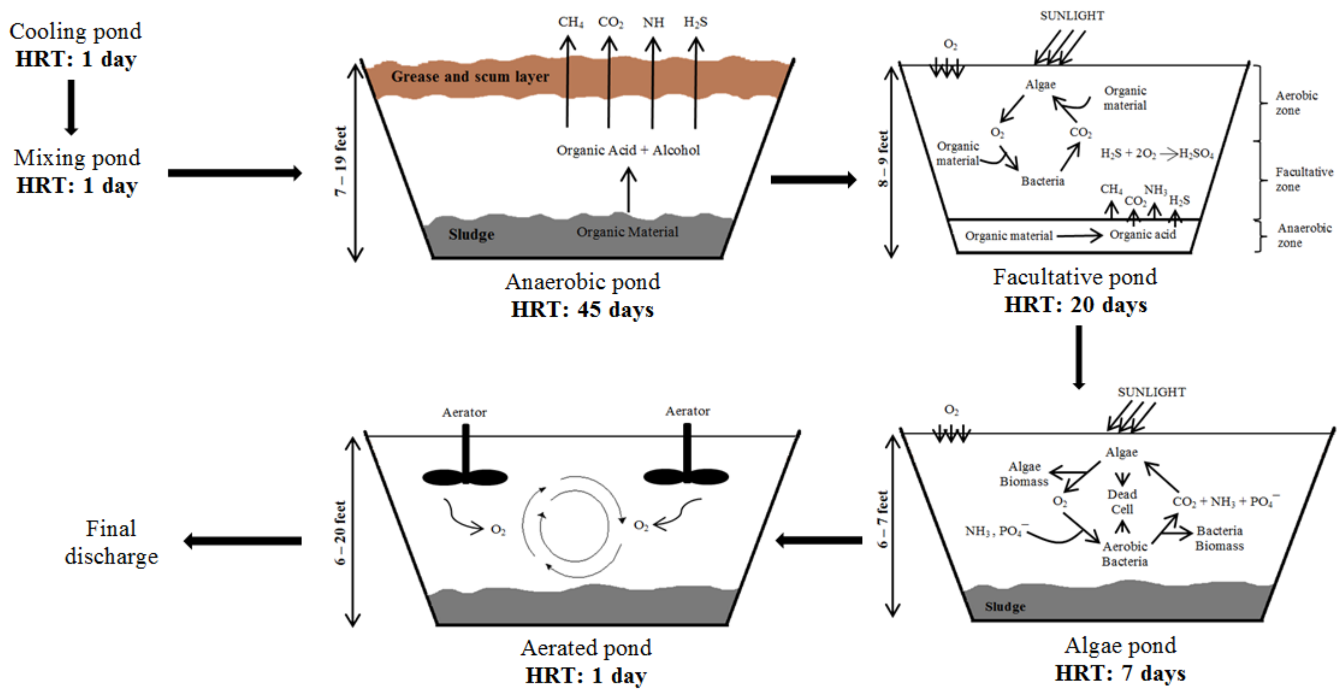


Figure 1 Layout plan for POME wastewater treatment plant. Adapted from [19]

The physical and chemical modifications on natural adsorbents are essential in order to enhance the number of active sites, surface area and pore volume that will eventually increase their adsorption capabilities. In addition, modifications are crucial to improve the selectivity of natural adsorbents towards contaminants in POME. For example, Wafti *et al.* [24] reported that physical modification on activated carbon obtained from palm oil empty fruit bunch has increased its BET surface area, total pore volume and pore size value from 231.52 m^2/g, 0.18890 cm^3/g and 3.67 nm to 347.043 m^2/g, 0.4482 cm^3/g and 5.16 nm, respectively. They also noted that the modified activated carbon demonstrated a better performance in reducing BOD, COD and SS up to 90%. Meanwhile, Mohammed and Chong [25] obtained a significant increase in BET surface area of banana peel following a chemical treatment using methanol. The BET surface area was reported to increase from 24.2572 m^2/g to 168.3648 m^2/g and the maximum removal of POME colour was also increased from 61.111% to 96.464%, respectively. Lam *et al.* [26] assessed the potential of biochar derived from orange peel to treat POME. They obtained a removal efficiency of more than 60% for BOD, COD, total suspended solid (TSS) and oil and grease (O&G). As discussed by Enaime *et al.* [27], several parameters such as physico-chemical properties, solution pH, adsorbent dosage and temperature of the medium might affect the adsorption of pollutants on biochar. Therefore, intensive studies on properties of biochar are necessary in order to obtain maximum adsorption capacity. Additionally, unmodified natural materials have also been studied by many researchers for POME treatment.

Table 2 summarises recent studies on application of bioadsorption technique for POME treatment. The bioadsorption technique was based on static adsorption process. For each bioadsorption study, concise information with regards to physical characteristics of adsorbents such as surface area, pore diameter, pore volume and particle size range are reported. In addition, information related to optimum experimental conditions are also described.

Table 2 POME treatment by bioadsorption

Absorbent	Characteristics of adsorbent	Operation conditions	Removal performance	References
Cocoa peel	Water content: 9.89% Ash content: 0.52% Volatile content: 84%	pH: 2 Contact time: 3 h Shaking speed: 200 rpm Dosage: 1.5 g	Oil: 80.88% Colour: 83.45%	[28]
Natural banana peel	Surface area: 24.2572 m^2/g	pH: 2 Contact time: 24 h Stirring speed: 200 rpm Dosage: 30 g	Colour: 61.111% TSS: 90.278% COD: 99.468%	[25]
Methylated banana peel	Surface area: 168.3648 m^2/g	pH: 2 Contact time: 24 h Stirring speed: 200 rpm Dosage: 30 g	Colour: 73.737% TSS: 91.667% COD: ~ 100%	[25]
Banana peel activated carbon	Surface area: 875.2914 m^2/g	pH: 2 Contact time: 24 h Stirring speed: 200 rpm Dosage: 30 g	Colour: 96.464% TSS: ~100% COD: ~100%	[25]
Coconut shell activated carbon	Mesh size: 8 x 30 Iodine number 1000	pH: 8 Contact time: 48 h Stirring speed: 150 rpm Dosage: 5 g	Colour: 61% TSS: 39% COD: 66%	[29]
Activated cow bone powder	Surface area: 248.398 m^2/g Pore diameter: 2.7226 nm Pore volume: 0.06235 cm^3/g Particle size: 1 mm	pH: 4 Contact time: 24 h Shaking speed: 50 rpm Dosage: 12.5 g/L	Cd: 69.30% Pb: 78.89%	[30]
Activated cow bone powder	Bulk density: 0.63 g/mL Solid density: 3.24 g/mL Porosity: 73.9% Length: 0.777 µm Particle size: 150 µm	pH: 7 Contact time: 150 min Shaking speed: 150 rpm Dosage: 0.025 mg/L Temperature: 30 °C	COD: 71%	[31]
Coal bottom ash-HCl	Surface area: 44.15 m^2/g Pore volume: 0.1535 cm^3/g Pore width: 139.02 Å	pH: 6 Contact time: 18 h Stirring speed: 160 rpm Dosage: 4.2 g	Colour: 81.15%	[32]
Palm oil empty fruit bunch activated carbon	Surface area: 937 m^2/g Microporous surface area: 871 m^2/g Mesoporous surface area: m^2/g Pore volume: 0.2837 cm^3/g Pore size: 2.0 nm	Contact time: 24 h Stirring rate: 150 rpm Dosage: 9% w/v	BOD: 88% COD: 98% SS: 96%	[24]
Montmorillanite	Surface area: 240 m^2/g	pH: 7 Contact time: 60 min Stirring speed: 300 rpm Conc. of POME: 25% Dosage: 4 g/L	> 95% of COD, TSS and colour	[33]
Natural zeolite	Surface area: 30-60 m^2/g	pH: 7 Contact time: 120 min for Zn and 180 min for Fe and Mn Stirring speed: 120 rpm Dosage: 25 g	Fe: 64.601% Zn: 53.644% Mn: 52.446%	[34]

(continue)

Table 2 *(continues)*

Absorbent	Characteristics of adsorbent	Operation conditions	Removal performance	References
Amino-functionalised silica Nanoparticles	Particle size: 500-600 nm Surface area: 148 m^2/g	pH: 7 Dosage: 0.25 g Temperature: 30 °C	COD: > 90%	[35]
Esterified sago bark	NR	pH: 4.18 Contact time: 24 h Stirring speed: 200 rpm Dosage: 2 g Temperature: 30 °C	Oil: 80.23%	[36]
Oil palm trunk	Surface area: 95.92 m^2/g Pore volume: 0.05 cm^3/g Micropore volume: 0.04 cm^3/g Average pore size: 8.30 nm	pH: 8 Contact time: 12 h Stirring speed: 150 rpm Dosage: 3 g	COD: 49.5%	[37]
Palm kernel shell activated carbon	Surface area: 566.27 m^2/g	pH: 8 Contact time: 120 h Stirring speed: 160 rpm Dosage: 30g	COD: 94% Colour: 100% Tannin-lignin: 96%	[38]
Palm oil mill boiler ash- microwaves irradiated	Surface area: 163.12 m^2/g Pore volume: 0.16 cm^3/g	pH: 2 Contact time: 5 h Stirring speed: 90 rpm Dosage: 15 g	Colour: 92.31%	[39]
Oil palm mesocarp fiber	Surface area: 494 m^2/g	pH: 9 Contact time: 24 h Stirring speed: 150 rpm Dosage: 10 g/L Temperature: 35 °C	COD: 69% SS: 96%	[40]

NR not reported, *BOD* biochemical oxygen demand, *COD* chemical oxygen demand, *TSS* total suspended solids, *O&G* oil and grease, *SS* suspended solids.

2.3 Activated Sludge

Activated sludge process is generally used for the secondary biological treatment in wastewater purification in which microorganisms metabolise suspended and organic solids in settling tanks or basins. These organisms are cultivated in basins, where they receive soluble oxygen and nutrients from the wastewater [41,42]. The activated sludge is normally separated from the water to a tank called clarifier.

Wun *et al.* [43] investigated the optimum operation conditions that might affect the treatment efficiency using anaerobic treated POME based on F/M ratio of 0.3 kg BOD/kg of mixed liquor volatile suspended solids (MLVSS). The optimum conditions for the treatment were reported as: pH 6.5 ± 0.1, 48 h of hydraulic retention time, 650 ± 20 mg/L of organic loading rate, 2000 ± 200 mg/L of initial MLVSS, 10 days of solid retention time and 50 mg/L of molasses concentration. With the higher COD and BOD removal ranged from 62-68% and 60-65%, respectively.

In order to enhance the activated sludge process, yeast-extract and dairy-waste was augmented into activated sludge by Abdulsalam *et al.* [44] and they studied the performance efficiency for anaerobically-treated POME. At an organic loading rate of 0.895 g COD/ L day, a remarkable COD and TSS removal performance showed a reduction of 92.58% and 96.89% that was obtained after 31 days of retention, respectively, while 57.99% and 46.25% were obtained for conventional sludge after retention for 87 days, respectively. For colour removal, modified sludge showed the highest removal of 63.45% at 5 L/min aeration in 36 h of retention time compared to conventional only 37%. This was discussed due to aggressively adaptive biomass that provides synergistic larger active sites for effectual xenobiotic degradation of various recalcitrant pollutants compounds.

2.4 Microorganism and Plant

Biological treatment methods use microorganisms such as fungal, algae and bacteria to break down and remove organic matter from wastewater. Bala *et al.* [45] investigated the ability of bacteria isolated by sequencing of 16S rRNA gene for the reduction of O&G and TSS in POME. The results indicated that the strain *Bacillus cereus* 103PB was the most effective bacteria with 85.14% and 71.63% of O&G and TSS removal after 5 days of treatment. Meanwhile, pH was reported to increase from 4.74 (raw) to 8.01 after the treatment with strain 103PB. Chaijak *et al.* [46] examined the termite-associated yeast *Galactomyces reessii* to optimise the removal of phenol in POME. The optimum conditions indicated incubation time of 7 days, culture concentration of

30% and concentration $CaCO_3$ of 5% as the most applicable parameter for remediation of phenol in raw POME treatment, which were optimised by using a Box-Behnken experimental design. In addition, the *G. reessii* showed high performance for phenolic removal of 88.69% under optimum condition.

Neoh *et al.* [47] have isolated bacteria culture from industrial sludge and used them for anaerobic bioremediation of POME. By using streak plate method, 23 bacteria were successfully isolated, however only *Ochrobactrum sp.* showed a great performance in degrading kraft lignin (KL) and thus were further selected for POME treatment. They reported a high COD reduction of 71% with removal rate of 1385 mg/L/day, which was 12.3 times more effective than conventional treatment (ponding system). Moreover, the bacteria were also reported able to reduce ammoniacal nitrogen by 60% and total polyphenolic by 55% within 6 days treatment period and involved lignocellulolytic enzymes.

In another study, Neoh *et al.* [48] studied the potential production of lignocellulolytic enzymes by fungus *Curvularia clavata,* for achieving a complete degradation of POME. The remarkable reductions in POME parameters of COD, BOD_3, total polyphenolic and ammoniacal nitrogen were obtained at 67%, 45%, 50% and 61%, respectively. Additionally, they noted that *C. clavata* exhibited a 314.3 U/mL and 3569 U/mL of xylanase activities production in raw POME and in fermentation of oil palm empty fruit bunch, which reflect its ability to degrade recalcitrant pollutant.

Four different genes of bacteria (*Pseudomonas fluorescens, Flavobacterium sp., Micrococcus sp., and Bacillus subtilis*) and six different species of fungi (*Aspergillus niger, Aspergillus tamari, Aspergillus sp., Penicillium sp., Trichoderma sp.,* and *Mucor sp.*) were isolated by Nwuche *et al.* [49] in order to examine the POME treatment efficiency with single strain and mixed cultures of bacteria and fungi. They reported that POME treated with single strain has resulted in removal of 81% of O&G, 83% of COD and 86% of TSS, respectively. Meanwhile, O&G was not detected, COD removal of 98% and TSS reduction of 81% following mixed culture treatment of POME. They also noted that the effects of pH, temperature and dilution concentration significantly influenced the treatment. The optimum pH and temperature was reported as 4 and 40 °C, respectively.

POME wastewater, dump site and palm wine were selected for isolation of seven types of yeast, which later were used for POME treatment under scalable conditions by Iwauagwu and Ugwaanyi [50]. From seven yeasts that were successfully isolated, the L31 species was reported to give the highest removal in COD at 83% after 96 hrs, while SP5 achieved the optimal COD removal at 73% after 72 hrs. In another study, Soleimaninanadegani and Manshad [51] have isolated four different bacteria, namely *Micrococcus sp.*, *Bacillus sp., Pseudomonas sp.* and *Staphylococcus aureus,* and six fungi, namely *Aspergillus niger, Aspergillus fumigatus, Candida sp., Fusarium sp., Mucor sp.* and *Penicillium sp.* for biodegradation of POME. The results indicated that the isolated microorganisms effectively degraded the BOD in the range from 23,400-52,100 to 15,500-16,800, 80,100-95,000 to 12,000 for COD, and 486 to 180 for colour, respectively.

Wastewater treatment using plants becomes more significant and necessary to obtain a simple, reliable and cost-effective treatment. In order to achieve a high standard quality of POME discharge, Kamyab *et al.* [52] investigated the feasibility of duckweeds (*Lemma minor*) and algal (*Chlamydomonas incerta*) for bioremediation of POME. Three different continuous flow duckweeds-algal treatment systems, namely *L. minor*, *Chlamydomonas* and their combination were used in the remediation experiment. They reported the performance for removal efficiencies of COD, nitrate (NO_3^-), ammonical nitrogen (NH_3-N) and phosphate (PO_4-P) for *L. minor* (1.7%, 6.3%, 11.3% and 66.28%), *Chlamydomonas* (3.8%, 12.5%, 3.7% and 66.32%) and its combination (4.4%, 12.5%, 10.4 and 70.47%), respectively, on the 14th day of experiment.

Kadir *et al.* [53] examined the phytotoxity ability of *A. pinnata* and *L. minor* to tolerate with POME under varied dilution concentrations (100%, 75%, 50% and 25%) and their ability to produce dischargeable POME wastewater. After 5 days of treatment in 25% dilution concentration of POME, the maximum removals of POME parameter by *A. pinnata* for BOD, COD, phosphate, nitrates and ammonia were determined as 70.5%, 63.0%, 65.4%, 53.8% and 51.0%, respectively while removal by *L. minor* was reported as 54.0%, 61.0%, 61.4%, 31.6% and 9.8%, respectively. They also observed that after 5 days of phytotoxicity exposure mostly *A. pinnata* was unable to survive under dilution concentration of 25% of treated POME as compared to *L. minor* only 5% changed the colour appearance to white, which indicates that the plant has died in 100% treated POME. They concluded that *A. pinnata* has better performance and capability in the treatment of POME than *L. minor* in respect of water quality although *L. minor* has a powerful act of resistance in the highly number of nutrients and organic carbon content.

Darajeh *et al.* [54] used vetiver grass (*Chrysopogon zizanioides* L.) to treat POME in order to decrease BOD and COD values under low and high concentrations of POME. The BOD and COD removal at high concentration of POME were reported as 62% and 39%, while at low concentration were determined as 96% and 94%, respectively using 30 tiller of vetiver. Tan *et al.* [55] conducted a feasibility study on phytoremediation of POME using *Eichhornia crassipes* by investigating the parameter effects of pH, plant to POME ratio and retention time. The maximum BOD removal of 92.78% was achieved at pH 4 with a plant to POME ratio of 1:20 kg/L within 21 days of retention time. The highest COD removal of 25.24% was measured at pH 6 with plant to POME ratio of 1:20 kg/L after 14 days of retention time.

Soetrisnanto and Hadiyanto [56] utilise two plant species, namely water lettuce (*Pristia stratiotes*) and algae (*Spirulina sp*.) to reduce COD and nutrients for phytoremediation of POME with variables of retention times and activated sludge concentration. The retention time was set from 1-5 days and activated sludge to POME ratio was in the range of 35-60% (v/v). The results revealed that in the first remediation process water lettuce successfully reduced the COD content up to 39.1-59.66%. Meanwhile, 17.73-30.78% of nitrogen and 6.14-18.46% of phosphorus was removed from the POME sample. At the second remediation process using *Spirulina sp.* algae, about 90% of nutrients were absorbed.

POME treatment based on phytoremediation technology using water hyacinth (*E. crassipes*) has been conducted by Chukwunonso *et al.* [57] in order to reduce the pollution load of the POME. Results indicated that the reduction of BOD and COD at POME dilution of 10% were 56% and 41%, respectively while at dilution of 50% the removal dropped to ~0% and 4%, respectively. In general, the content of COD, nitrogen and phosphorus in raw POME decreased with the increase in retention time and POME concentration using phytoremediation technology.

2.5 Aerobic Biodegradation

In aerobic biological treatment, oxygen is present throughout the process in order to promote the photosynthesis process of the microorganisms to decompose organic substances in the wastewater. An aerobic treatment by using a sequencing batch reactor system was studied by Chan *et al.* [58] in the laboratory to evaluate factors that might affect the treatment performance with respect to BOD, COD and TSS removal efficiencies. The study was conducted at pH 8.25-9.14 and dissolved oxygen concentration of 1.5-6.4 mg/L. They observed a maximum removal efficiency of 96% for COD, 98% for BOD and 99% for TSS at optimum range of organic loading rates of 1.8-4.2 kg COD/m^3 day, sludge loading rate (SLR) of 2.5-4.6 kg TSS/m^3 day and MLVSS concentration of 22,000-25,000 mg/L, respectively. They noted that the experimental parameters such as temperature, DO, pH, MLVSS, OLR and SLR significantly contributed to the performance of the aerobic sequencing batch reactor system. In addition, the stability sludge in their studies showed excellent settling properties with average sludge volume index (SVI) of 65.

In the context of palm oil industry, high process wastewater temperatures prevail and thus water treatment needs to take place under thermophilic conditions to reduce the capital cost. An investigation on aerobic biological treatment was conducted by Chan *et al.* [59] at thermophilic condition to identify the optimum operation conditions to achieve the best treatment. The optimum operation conditions for this study were reported as: organic loading rate of 2.5 g COD/Lday, MLSS concentration of 27,000 mg/L, DO concentration of 2.0 mg/L and settling time of 2 h. Under optimal conditions, the removal efficiencies ranging from 63.8-86.3% for COD, 65.5-87.0% for BOD and 79.2-89.1% for TSS.

2.6 Integrated/hybrid Treatment

Since each POME remediation technique has its own advantages and disadvantages, the combination of two or more techniques might increase pollutant removal efficiency. As shown in Table 2, the removal efficiency of target pollutants for POME following integrated/hybrid treatment process almost achieved 100%. The combination of two different techniques has successfully overcome the drawback of another technique. For example, Ahmad *et al.* [60] treated POME using a combination of coagulation/flocculation and membrane filtration techniques. The coagulation/flocculation treatment was purposely to increase the size of particle, which is crucial in order to reduce the membrane fouling, a major problem in membrane filtration treatment. The total removal of SS, O&G and COD was reported as 99%, 99% and 98%, respectively.

Meanwhile, Parthasarathy *et al.* [61] conducted a study on application of hybrid coagulants and AOPs for remediation of POME. They noted that single coagulation treatment by using chitosan (2500 mg/L) resulted in maximum COD and TSS reduction of 70.22 ± 0.23% and 85.59 ± 0.13%, respectively. However, after addition of $FeSO_4$ (2500 mg/L) along with chitosan (2500 mg/L) the pattern of reduction seem to increase in the TSS removal (98.7 ± 0.06%) and decrease in the COD removal (62.61 ± 2.41%). A continuous increment in the removal efficiencies of COD at 82.82 ± 1.71% and TSS at 89.92 ± 0.48% was observed after chitosan was hybrid with H_2O_2 (500 mg/L). Finally, integrated treatment of coagulation using chitosan (2500 mg/L) with Fenton oxidation ($FeSO_4$ of 2500 mg/L and H_2O_2 of 500 mg/L) showed a higher removal percentage of 73.08 ± 4.11% for COD with completely TSS removals.

Table 3 summarises the studies on integrated technique for POME treatment. The results of combining techniques show an improvement in the production of high quality water in which the target contaminant is almost completely removed. Therefore, combination strategies are an important aspect for the development of efficient technologies for remediation of POME and to improve the conventional method related to retention time, cost and material recovery.

Table 3 Integrated hybrid treatment of POME

Treatment		Operation conditions	Removal performance	References
First stage	Second stage			
Coagulation (alum)	AOP (UV/H_2O_2)	Alum dosage: 5 g/L H_2O_2:COD : 2:1 UV power: 30 W	Colour: 98.25%	[62]
Coagulation/ flocculation (*Moringa oleifera*)	Membrane filtration (ceramic UF membrane, PVDF UF and TFC RO)	pH: 5 MO dosage : 6000 mg/L	SS: 99% O&G: 99% COD: 98%	[60]
Coagulation/ flocculation (chitosan, ferric sulfate)	AOP (H_2O_2, Fenton oxidation)	Chitosan dosage: 2500 mg/L $FeSO_4$ dosage: 2500 mg/L H_2O_2 dosage: 500 mg/L	TSS: 100% COD: 73.08 ± 4.11%	[61]
Anaerobic bioreactor	Membrane filtration(PAC-PES membrane)	Temperature: 45 °C Sludge retention time (SRT): 30 days Hydraulic retention time (HRT): 6 days PAC size: 100.337 ± 1.34 µm at 5 g/L dosage	COD: 78.53 ± 0.66% Permeate flux: 32.09 ± 1.25 L/m^2h	[63]
Biological treatment (microbial fuel cell)	Anaerobic membrane bioreactor	Temperature: 45 °C	COD: 97.66 ± 0.41%	[64]
Ultrasonic	Membrane filtration	OLR: 15 kg COD/m^3/day	COD: 98.5%	[65]
Biological treatment (anaerobic and aerobic)	Membrane filtration (UF/RO)	Scale: pilot study Monitoring period: a year	COD: ~100% BOD: ~100% SS: 100% Colour: 100%	[66]

3.0 CONCLUSIONS, RECOMMENDATIONS AND FUTURE PERSPECTIVES

Extensive studies on the possibilities for converting the sludge generated in the biological treatment to organic fertiliser should be carried out in order to reduce the amount of sludge waste dumped in landfill. The plant's flexibility, reliability, capital expenditures and operating expenses are crucial factors in the selection of the treatment process as well as the environmental tolerance of the material used in the process. Therefore, comprehensive studies related to operational cost, limitations and factors/parameters that might affect the treatment process of POME should be the main focus in the future. This information will be beneficial to researchers and industrial workers. Thus, identifying the synergy effect among the treatment processes, materials used, operational cost and conditions is indeed crucial in order to achieve high performance in contaminant removal. Additionally, the two major global palm oil production countries are situated in tropical regions that are warm throughout the year. Therefore, wastewater treatment by the process of evaporation may be suitable and can be introduced for these countries. Generally, there are two types of evaporation techniques that can be used to treat POME, namely: (i) natural evaporation pond using sunlight/solar and (ii) mechanical evaporation equipment. The evaporation technique can be very useful to obtain zero liquid discharge since all water molecules from effluent will escape into the atmosphere as water vapour. The remaining solid sludge that contains high amounts of nutrients such as nitrogen, phosphorus, calcium, magnesium and potassium can be used as fertiliser for plants after the evaporation process.

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