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PERFORMANCE EVALUATION OF POME TREATMENT PLANTS

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ABSTRACT

Palm Oil Mill Effluent (POME)'s nutrient composition and its ensuing removal from the wastewater is rarely reported in contrast with organics removal. Thus, the efficiency of several Industrial Effluent Treatment Systems (IETS) in nutrient removal are studied. Many laboratory- and full-scale studies have been constructed to examine the effectiveness of nutrient removal with a single technology. Therefore, this paper observed their efficiency after several unit processes were combined to perform, which generally occurred in the full-scale IETS. Total Nitrogen (T-N), Ammoniacal Nitrogen (A-N), and Total Phosphorus (T-P) were nutrient parameters investigated. IETS-3 with highest nutrient removal efficiency were 92.5% T-N, 94.5% A-N, and 93.5% T-P, which highlighted positive combination of ponding system, anaerobic digesters and extended aeration coupled with fixed packing in activated sludge aeration tank. Removal of biological nutrients need to move forwards with cradle-to-cradle waste management methodologies, which focus on sustainable recovery of essential nutrients via operative technologies.

Keywords: agro-based wastewater, biological nutrients removal, industrial effluent treatment systems, technology integration.

INTRODUCTION

The oil palm (*Elaeis guineensis*) is known to capable of producing 3.7 tonnes of oil per hectare annually, which is considered as the highest oil yielding perennial tree crop (Sundram *et al.* 2003). Oil palm was originated from the West Africa, and is recently a main plantation in countries like Indonesia, Malaysia, Nigeria, Thailand, Columbia, Benin, Cameroon and few others. In Malaysia, the industry plays the role as the nation economy's backbone, making the country the second largest world palm oil producer, after Indonesia (Lam and Lee, 2011). 424 palm oil processing mills throughout the country produced 92,917,496 tonnes of fresh fruit bunches (FFB) in year 2011 alone (MPOB, 2012). In general, high crop season happens from July to December while low crop season occurs from January to June. In year 2011, the oil palm bloom showed significant impact to land use pattern in Malaysia where oil palm plantations covered approximately 16% or 5 million hectares of total land use (MPOB, 2012). With planning and construction of more palm oil processing mills, the industry is expected to further expand and its outstanding achievement will continue to become a main source of wealth generation to the nation.

Attention on environmental sustainability have been focusing on the dynamic activities of the palm oil industry. Concerns on the upstream activities aroused through deforestation and damage of wildlife habitat, emissions of greenhouse gases (GHG), ecological issues, loss of soil fertility, misuse of pesticides and fertilizers, soil erosion, water resource contamination, and excessive of agricultural (DOE, 1999). Downstream processing problems are caused by the palm oil milling or extractions of crude palm oil activities. Palm oil processing mills discharge a highly detrimental wastewater known as the POME. The raw effluent is an acidic colloidal suspension, unpleasant smell, and has high content of biodegradable organic matter caused by the presence of unrecovered palm oil (Ahmad *et al.* 2009). The wastewater has high biochemical oxygen demand (BOD, 3 days at 30^{o}C) content, averages 25,000 mg L^{-1} which causes severe river water pollution if not well treated prior to discharge (Lam and Lee, 2011).

The environmental impacts of palm oil processing have led to certain misapprehension to the industry on ecosystem damage and environmental contamination. The industry has to improve in term of sustainability and being more environmental responsive in order to strive for continuous growth. To ensure the industry release acceptable level of pollutant to the waterways, land, and air, the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 and other environmental related regulations are well established in Malaysia. The Malaysian palm oil processing mills have commonly complied with the BOD 100 mg L^{-1} discharge limit (Ma, 1999a). Nonetheless, the Malaysian government is gearing towards to treat the effluent to 20 mg L^{-1} BOD (Ma, 1999a; MPOB, 2010).

Extensive research efforts have been made towards developing low cost, consistent, and effective POME treatment technologies. Conventional POME treatment involved ponding system or the waste stabilization ponds (anaerobic, aerobic, and facultative), closed or opened tank digesters, land disposal, and extended aeration (DOE, 1999). Several technologies and processes have been attempted on POME treatment and these studies provided affirmative and positive results. Among the reported technologies were aerobic digestions through activated sludge reactors, rotating biological contactors, bioreactors inoculated with fungi or bacteria, and sequencing batch reactors; anaerobic digestions via digestion tanks, up-flow sludge blanked reactors, anaerobic filters, anaerobic fluidized bed reactors, anaerobic baffled reactors, and expanded granular sludge bed reactor; physiochemical processes such as fenton-oxidation, silent discharge ozoniser, coagulation, and electrocoagulation; in addition to membrane filtration processes (Wu *et al.* 2010; Aris *et al.* 2008).

A great number of technologies, either from laboratory- or pilot-scale studies were known to successfully treat POME to certain degree of removal efficiency. However, unceasing POME-causing environmental issues in Malaysia and other palm oil producing countries have urged more studies to be conducted to get intuition into these technologies and determine any technological issues in our current POME IETS. In POME-treating laboratory-scale studies, most standalone technologies were shown efficient. Nonetheless, these technologies are usually combined in series to perform in full scale IETSs. No studies have been conducted to assess the effectiveness of these standalone technologies after technology integration. Besides, previous POME treatment literatures emphasized on organic pollutants removal. The recent work is implemented to investigate the effectiveness of unit processes combined in full-scale IETS treating POME for nutrients removal.

Methods

Three palm oil processing mills were voluntarily involved in this study to investigate the achievement of their IETS. All three mills are situated in the Johore state and within one hour journey from the University. IETS-1 is a high milling capacity private factory. The mill operated since 1996 and its milling activities included palm kernel processing, crude palm oil extraction, biomass generation, antioxidant extraction, fertilizer manufacturing and commercialization, as well as biogas collection and utilization. Its IETS was a comprehensive integration of various technologies designed to reduce the pollutant loads to satisfactory level. Both IETS-2 and IETS-3 were situated in the same area and approximately within 10 km radius away from a water treatment facility. These two factories were old and having middle milling capacity. Nonetheless, their IETS were upgraded and installed recently by third party suppliers (year 2011).

The IETS in this study incorporated conventional and polishing (or tertiary) unit processes. The conventional approaches included preliminary treatments (de-oiling, mixing, sedimentation), anaerobic treatments (acidification phase and methanogenic phase), and ponding systems (facultative ponds, algae ponds, anaerobic ponds, and aerobic ponds) whereas the polishing processes varies among each IETS. The processes involved are depicted as below:

IETS-1: Acidification ponds (2 units) → closed-tank anaerobic digesters (3 units) → aerobic pond → sequencing batch reactors (3 units) → extended aeration pond → clarifying ponds (2 units)

IETS-2: Anaerobic ponds (4 units) → algae ponds (4 units) → suspended packing in activated sludge aeration tanks, with complete mixing

IETS-3: Mixing ponds (3 units) → open-tank anaerobic digesters (9 units) → algae ponds (6 units) → extended aeration, coupled with fixed packing in activated sludge aeration tank

Sampling, interview, and discussion were performed at the palm oil processing mills. Pre-rinsed polyethylene containers were used to collect the POME samples from each treatment stages. All samples were kept in dark condition at 4°C and analysed in the laboratory within 48h. Interview sessions with the engineers, chemists, and IETS handling personnel were done with the prepared questionnaires to comprehend the mode of IETS operation. Discussions were aimed to understand the IETS design and other related information as listed in Table-1. On-site inspection for physical properties of the effluent (physical conditions, temperature, dissolved oxygen, and pH) were performed along with the sampling activities and documented in Table-2. POME samples were analysed on the following parameters: BOD, T-N, A-N, and T-P based on the Standard Methods (APHA, 2005).

Table-1. Basic information of the IETS.

Information	IETS-1	IETS-2	IETS-3
Location	Kota Tinggi	Kulaijaya	Kulaijaya
Management Background	Individual miller	Government-backed organization/company	Government-backed organization/company
FFB yield (tonnes of FFB per year)[a]	405,146	117,964	204,142
Year of operation commencement	1996	1968	1977
POME production (tonnes of POME per year)[b]	271,448	79,036	136,775
Operation (days per year)	312	348	348
Biogas collection facility	Yes	No	No
Effluent final discharge limit (mg L^{-1})[c]	100	100	100
Biological approach at the polishing stage	Suspended-growth processes	Attached-growth process with moving media / bed	Attached-growth process with fixed bed

[a] Calculated based on 13 years of FFB processed data provided by the palm oil processing mills.
[b] Estimated in accordance to the ratio of 0.67 tonnes POME per tonne FFB processed (Ma, 1999a; Ng *et al.* 2011).

[c] Based on the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 (Legal Research Board, 2008).

Table-2. Documented physical properties and water quality during sampling events (means ± standard deviations, n = 3).

Location	Degree of foaming condition[a]	Odour intensity[b]	T[c] (°C)	pH	Dissolved oxygen (mg L^{-1})
IETS-1					
the last acidification ponds	-[d]	5	51.53±6.15	5.16±0.20	0.19±0.05
discharge from the closed-tank anaerobic digesters	Moderate	6	41.03±1.35	6.84±0.35	0.02±0.05
the aerobic pond	-[d]	4	27.43±3.20	8.14±0.30	0.81±0.60
discharge from the sequencing batch reactors	Moderate	4	28.63±2.30	8.40±0.15	1.11±0.35
the extended aeration pond	Moderate	2	27.90±2.40	8.42±0.20	1.89±0.40
the last clarifying ponds	Moderate	2	28.40±3.00	8.50±0.25	2.33±0.25
IETS-2					
the last anaerobic ponds	-[d]	4	27.25±0.60	7.36±0.05	0.41±0.15
the last algae ponds	Low	2	28.67±0.65	8.91±0.10	1.50±0.60
discharge from the polishing system	High	2	30.37±1.05	8.62±0.30	2.27±0.60
IETS-3					
the last mixing ponds	Low	5	81.03±13.20	5.30±0.05	0.60±0.45
discharge from the open-tank anaerobic digesters	-[d]	6	32.57±0.80	7.41±0.55	0.07±0.10
the last algae ponds	High	2	29.23±0.70	8.85±0.10	1.30±0.10
discharge from the polishing system	High	2	28.90±0.60	8.66±0.50	3.33±0.90

[a] Degree of foaming condition – from low to high.
[b] Odour intensity – descripting from 0 (no odour) to 6 (extremely strong), in accordance to the Department for Environment, Food and Rural Affairs (2006).
[c] 'T' means temperature.
[d] '-' means no foaming.

Pollutant loads carried by the wastewater can be estimated based on the FFB production's information. An estimation method for pollution loads according to per tonne of FFB processed is given by Thanh *et al*. (1980). In this study, the estimation method was adopted for BOD, T-N, and T-P load calculation. In addition, removal rates were calculated for each technologies associated in an IETS in order to study the technology efficiency. Removal rates can be calculated by using equation (1) whereby C_{inf} is the concentration of pollutant measured at the influent and C_{eff} is the concentration of pollutant measured at the treated effluent (Santos, 2007).

$$\text{Removal rates} = [(C_{inf} - C_{eff}) / C_{inf}] \times 100 \quad (1)$$

RESULTS AND DISCUSSION

Various unit processes (or technologies) are generally combined and connected in series for optimal effluent treatment in order to tackle the complex wastewater characteristics. While each processes are designed for certain purposes, the number and type of unit processes depends on the intended quality of treated effluent and more practically, meeting the discharge limit. Physical and biological processes are integrated to eliminate the organic and readily biodegradable compositions in the POME (DOE, 1999). Before the secondary biological processes begins, raw effluents are firstly treated in physical pre-treatment steps. Screening, sedimentation, and oil traps or de-oiling tanks are among the common pre-treatment phases. Organic composition of POME is treated via ponding systems, which are commonly wastes stabilization ponds. The process required very long hydraulic retention time (HRT) to stabilize the wastewater. It is also implemented for settling of suspended solids or sludge (Wong, 1980). Microorganisms such as the archaea, bacteria and algae are involved which resulted in the generation of excess sludge or biomass caused by their metabolic activities. To ensure the biological system performs satisfactorily, de-sludge activities are needed. Chemical substrates and other physical conditions are needed for the growth and survival of biological cells before they ultimately decay (Wong, 1980). Acidification ponds, aerobic ponds, algae ponds, anaerobic ponds, cooling ponds, facultative ponds, maturation ponds, mechanically-assisted oxidation pond, and mixing ponds are among the common types of waste stabilization ponds (lagoons) in application.

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Table-3. Removal efficiencies of unit processes in the IETS.

Location	Removal Rates (%)			
	BOD	T-N	T-P	A-N
IETS-1				
closed-tank anaerobic digesters	33.5	32.5	32.0	↑ 62.0[a]
aerobic pond	91.0	↑ 3.0[a]	70.5	22.0
sequencing batch reactors	1.5	38.5	0.0	5.5
extended aeration pond	67.0	70.0	60.0	81.0
clarifying ponds	0.0	43.0	0.0	48.5
IETS-2				
algae ponds	84.5	40.0	↑ 6.0[a]	64.0
suspended packing in activated sludge aeration tanks, with complete mixing	80.5	89.0	19.0	86.0
IETS-3				
open-tank anaerobic digesters	67.5	44.5	74.0	↑ 89.5[a]
algae ponds	93.5	53.0	64.5	71.0
extended aeration, coupled with fixed packing in activated sludge aeration tank	81.0	72.0	30.0	89.5

[a] The concentration of pollutant have increased instead of reduction.

Table-3 showed the nutrients' removal rates obtained by each stages or technology in the IETS. The ponding system is preferred for its reliable and stable performance, low cost of construction and operation, and mostly implemented in all mills because of vast land availability. The system is capable to reach satisfactory degree of BOD reduction (Ma, 1999b). In this study, the statement is proved where BOD reduction exceeded 80% in all ponding systems of IETS-1 (91.0%), IETS-2 (84.5%), and IETS-3 (93.5%). Before entering the aerobic pond, effluent exiting the closed-tank anaerobic digesters and entered a series of anaerobic ponds in IETS-1. Anaerobic ponds were designed at 7 meters deep to prevent production of the oxygen in the system which generated by penetration of sunlight and any photosynthetic activity (DOE, 1999). The aerobic pond is aerated via surface aerator. In the aerobic ponds, high BOD reduction achievement is estimated to achieve between ranged of 74 to 81% (Wong, 1980). Raw POME in IETS-4 was anaerobically treated in open-tank digesters and entered the facultative ponds before further treated in algae ponds to auxiliary reduce its organic composition. Facultative ponds usually consisted of three operational zones, which are the aerobic upper layer, facultative middle layer, and the anaerobic sludge layer. Photosynthetic activity of algae produces oxygen for aerobic bacteria for organic decomposition. Algae pond commonly extended the duration for facultative treatment or offers maturation for higher degree of treatment.

Highest T-N removal was noticed in IETS-2 (89.0%), followed by IETS-3 (72.0%) and lastly in IETS-1 (70.0%). The technologies that caused these outcomes were suspended packing in activated sludge aeration tanks, with complete mixing in IETS-2; extended aeration, coupled with fixed packing in activated sludge aeration tank in IETS-4; and extended aeration pond in IETS-1. The common similarities proposed that activated sludge systems are efficient to promote T-N removal. According to Tchobanoglous *et al*. (2004), the quantity of nitrogen removed always indicated the quantity needed by the suspended biological system. This proposed that high nutrients level is needed for the performance of these technologies. Besides, nitrogen removal happened at aerobic zone in which biological nitrification takes place. The study strengthened the proclamation where all three reported technologies are aerated processes like the presence of complete mixing, extended aeration, and sequencing batch reactors. These technologies are usually not the final treatment stage as some anoxic volume or time is required to allow the occurrence of biological denitrification process to achieve the objective of complete nitrogen removal (Tchobanoglous *et al.* 2004).

Biological phosphorus removal happened at highest efficiency in IETS-3 (74.0%) and IETS-1 (70.5%). The similarities noticed are the existence of anaerobic digesters prior to the aerobic or facultative treatment of POME. The finding is accurate as stated in the literature where biological phosphorus removal process configurations consisted basic steps of anaerobic zone followed by an aerobic zone (Tchobanoglous *et al.* 2004). Both IETS-3 and IETS-1 combined anaerobic digesters in their treatment processes followed by the conventional ponding system. Nutrients removal are normally more visible in polishing stages of POME treatment whilst highest removal does not necessarily happened at these stages. T-P nonetheless is rarely studied due to the parameter is not regulated in the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 (Legal Research Board, 2008). Both T-N and T-P are essential to assure the biological systems operate well, despite of the advertency. Eutrophication or disruption to the industrial water recycle applications are usually caused by inappropriate handling and discharging the improperly treated wastewater to waterways.

Ammoniacal-nitrogen distribution is a function of pH of the wastewater. Wastewater's pH, which is below the value of 7 caused the ammonium ion appears principally in raw POME. As described in Table-3, the level of A-N in anaerobic digesters increased by 62.0% and 89.5% for IETS-1 and IETS-3 respectively. Protein is an example of components that produce A-N during biodegradation of biological cells in the anaerobic stages.

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The produced A-N will integrate with water and carbon dioxide to form ammonium bicarbonate that caused increment of POME alkalinity during the treatment process (McCarty, 1964). Increasing the degree of alkaline or buffering capacity will then increase the pH of acidic raw POME to achieve suitable treatment. Another explanation regarding the intensification of A-N in anaerobic treatment was the formation of ammonia from organic nitrogen. During waste degradation, orthophosphate will also increase for the same reason. The formation was meant for biological growth with anaerobic condition (McCarty, 1964; Kobayashi *et al.* 1983). A-N is showed progressively removed along with highest removal rate happened at IETS-3 (89.5%), followed by IETS-2 (86.0%) and IETS-1 (81.0%) after anaerobic digestions and further treated in following integrated technologies. The technologies experienced of A-N removal were extended aeration pond in IETS-1, suspended packing in activated sludge aeration tanks, with complete mixing in IETS-2, and extended aeration, coupled with fixed packing in activated sludge aeration tank in IETS-3. Other proficient A-N removal technologies involved breakpoint chlorination, ion exchange, air stripping, reverse osmosis, and microfiltration (Tchobanoglous *et al.* 2004).

Almost all studied technologies on POME showed high removal rate and proposed their applications in the palm oil processing mills. These technologies, nonetheless in this study, were observed to behave oddly or even not operating well after integrated with other processes. Technologies implemented to the IETS generally operated differently compared to laboratory treatability studies. For example, the sequencing batch reactors are well-known for successful T-N and T-P removal (Tchobanoglous *et al.* 2004). Nonetheless, the technology is not operating well in IETS-1 with integration of aerobic digestion and extended aeration. Sequencing batch reactors are considered as complex processes design and the effluent quality is rely on the decanting facility (Tchobanoglous *et al.* 2004). Researchers, millers, and technology providers should show their concern in technology integration as it is a complicated design consideration to attain optimal POME treatment. Skilled operation and maintenance are another aspects contributed to the effectiveness of technology applied in the palm oil processing mills.

Table-4. Overall removal rates of the IETS and their respective pollutant loads.

Parameters	IETS-1	IETS-2	IETS-3
BOD Loads[a], kg BOD hr^{-1}	2,034.8	531.2	919.2
T-N Loads[a], kg T-N hr^{-1}	46.8	12.2	21.1
T-P Loads[a], kg T-P hr^{-1}	26.6	7.0	12.0
Overall BOD Removal, %	98.0	97.0	99.5
Overall T-N Removal, %	92.5	93.5	92.5
Overall T-P Removal, %	88.0	14.0	93.5
Overall A-N Removal, %	88.5	95.0	94.5

[a] The pollutant loads are based on ratio described in Thanh et al., (1980).

Figure-1. The IETS (IETS-3) showing overall highest removal efficiencies of BOD and nutrients. The polishing system consists of (a) extended aeration, (b) & (c) fixed packing media submerged in the activated sludge aeration tank, and clarifiers before final discharge. (d) showed the plastic media used in the IETS.

IETS-3 showed highest removal efficiency with BOD 99.5%, T-N 92.5%, T-P 93.5%, and A-N 94.5% as shown in Table-4. This achievement showed the matured technology integration of the traditional ponding system, open-tank anaerobic digesters, and extended aeration, coupled with fixed-packing in activated sludge aeration tank which is the polishing stage. Individually, the open-tank anaerobic digesters contributed notably in organics removal and T-P reduction, the conventional ponding system catered for organics removal, whereas the polishing stage contributed to organics, T-N and A-N removal. To define the polishing technology implemented in IETS-3, it is principally an attached growth process with fixed media. Biofilm grow and attach to the specially-customized high surface area plastic media. The carriers are restricted in cages in a pilot-scale bioreactor plant suspended with activated sludge. Secondary effluent enters the extended aeration chamber before undergo further treatment in the bioreactor plant.

Pollutant loads are crucial design and operating parameter that influence the treatment efficiency and generally, operation of the biological processes (Tchobanoglous *et al.* 2004). Highest loads were observed in IETS-1, followed by IETS-3, and lastly IETS-2. Nonetheless, these IETS are showing high pollutant removal efficiencies, which is probably due to the implementation of biological treatment systems. Biological treatment systems are able to manage and tolerate wastes at specific volumetric loading rates and withstand organic shocks without any substantial long term detrimental effects (Saravanane and Murthy, 2000).

Various studies were performed with focus to organic destruction to obtain the BOD 100 mg L^{-1} discharge limit. More ambitious research works are on-going to extensively bring down the effluent to BOD 20 mg L^{-1}, colour abatement, and recycle of sludge. Nutrients removal simultaneously happened as POME treatment technologies reduce the organic composition of effluent. Nutrients recovery is believably a more significant issue to be focussed on currently. The remaining nutrients in effluent or sludge are useful for potential applications after treating POME that fulfil the discharge standard. Nutrient ratios of the effluent are fairly comparable to the nutrient ratio requirement of oil palm, which opened the prospect to apply the recycled treated effluent to oil palm fields with the aim of controlled land application techniques (Ma, 1999b). Studies were conducted to apply vermicomposting technique as a sustainable POME management option to reuse the remaining nutrients as fertilizer in POME. Vermicomposting is a nutrient rich product which can enhance the soil condition in oil palm plantations (Rupani *et al.* 2010). Anaerobically treated POME and sludge were implemented on empty fruit bunches to enhance the co-composting treatment process in certain mills. POME sludge was used as nutrient source for the composting treatment as it has high content of calcium (Ca), potassium (K), magnesium (Mg), and phosphorus (P) (Baharuddin *et al.* 2010).

CONCLUSIONS

IETS are constructed to treat POME to adhere to the national discharge limit. Nutrients and organics removal happened concurrently via varies biological and physical processes joined in a treatment plant. The study emphasized the effective achievement of attached-growth biological wastewater treatment process with fixed media, as IETS-3 was determined to operate effectively. Few technologies when operated individually in treatability studies operated effectively but showed implausible outcomes after combined to work in stages. Thus, in technology applications, extensive research is required for better POME management. Additionally, nutrients recovery need to be emphasized rather than nutrients removal.

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