EFFICIENCY OF NUTRIENTS REMOVAL FROM PALM OIL MILL EFFLUENT TREATMENT SYSTEMS

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ABSTRACT

While most studies concentrate on organic removal from palm oil mill effluent (POME), the resulting nutrient recovery and subsequent removal from the wastewater is infrequently described. Although sporadic research has been performed to investigate nutrient removal efficiency of a single technology, the efficacy after combined with other technologies, which usually happened in industrial effluent treatment systems (IETS) has not been thoroughly checked. Hence, this study assessed the effectiveness of four IETS having different technology combination in nutrient removal. Nutrients such as total nitrogen (TN), ammoniacal nitrogen (AN) and total phosphorus (TP) from POME of these IETS were analysed. Of the four IETS investigated, the combined ponding system, anaerobic digesters and extended aeration coupled with fixed packing in activated sludge aeration tank showed the highest nutrient treatment efficiency (92.5% TN, 94.5% AN and 93.5% TP). Moving forward, POME management should gear towards sustainable recovery of essential nutrients through operative technologies.

Keywords: agro-based wastewater, biological nutrients removal, biochemical oxygen demand, industrial effluent treatment systems (IETS), discharge limit, technology efficiency.

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INTRODUCTION

Oil palm (*Elaeis guineensis*) has been identified as the highest oil producing perennial tree crop capable of yielding 3.7 t of oil per hectare annually (Sundram *et al*., 2003). Originating from West Africa, oil palm is currently a major plantation crop in countries like Indonesia, Malaysia, Thailand, Nigeria, and Colombia. The industry is one of the pillars of Malaysia's economy, making the country the second largest world palm oil producer (Lam and Lee, 2011). In 2014 alone, 439 palm oil mills (POM) throughout the country processed 95 380 438 t of fresh fruit bunches (FFB) (MPOB, 2015). Low crop season falls from January to June whereas high crop season occurs from July to December in general. The oil palm bloom offered momentous impact to land use pattern in Malaysia *i.e.* oil palm land coverage stretched 5.39 million hectares or approximately 16.5% of total land coverage in year 2014 (MPOB, 2015). With more POM in planning and construction stage, the industry is anticipated to flourish further and its stellar performance will continue to become a major source of wealth generation to the nation.

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Dynamic activities of the palm oil industry from upstream to downstream processing have always drawn the attention and qualms on environmental sustainability. Anxieties on the upstream doings arises through deforestation and hence, destruction of wildlife habitat, ecological issues, greenhouse gas (GHG) emissions, soil erosion, loss of soil fertility, pesticides and fertilisers usage, water resource pollution, as well as agricultural run-off (DOE, 1999). Palm oil milling or extraction of crude palm oil triggers downstream processing problems. All POM discharge a highly detrimental wastewater known as the palm oil mill effluent (POME). The raw POME is an acidic colloidal suspension with unpleasant smell and has high content of degradable organic matter due to the presence of unrecovered palm oil (Ahmad *et al*., 2009). It has high biochemical oxygen demand (BOD, three days, 30°C) and chemical oxygen demand (COD) averaging 25 000 mg litre^{-1} and 50 000 mg litre^{-1} respectively which leads to serious river water contamination if not properly treated (Loh *et al*., 2013a).

Environmental impacts of POME discharge activities have unavoidably begot misconception to the industry. Palm oil has been negatively portrayed in some countries where some of the opposing interpretations positioned palm oil leading to ecosystem damage and environmental pollution. To strive for continuous growth, the industry has to work towards better sustainability and more environmental responsive. In Malaysia, the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 (Legal Research Board, 2008) and other environmental-related regulations are well demarcated to make sure the industry discharges acceptable level of pollutant to the waterways, land and air. The 'polluter pays' principle works well and the licensing system guarantees that only POM complying with the discharge regulations can continue their mill operation. Besides, the progressively more stringent BOD discharge limit in the pipeline has driven millers and research & development (R&D) focus towards better effluent treatment. The Malaysian POM have generally complied with the BOD 100 mg litre^{-1} discharge limit (Ma, 1999). However, the government is currently supporting and demanding better management of POME for further BOD reduction to 20 mg litre^{-1}. The new discharge limit covers environmental sensitive areas such as tourism areas of east Malaysia (Sabah and Sarawak state) and those locations in close proximity to water intake points (Loh *et al*., 2011; Liew *et al*., 2015).

The Malaysian perspective towards sustainable palm oil associating with POME is apparent through its collaboration with roundtable on sustainable palm oil (RSPO). Under the RSPO, environmental responsibility and conservation of natural resources and biodiversity is branded as one of the key principles to be accomplished. Other initiatives showing environmental commitments from the palm oil industry include renewable and sustainable bio-energies production from POME (Lam and Lee, 2011; Loh *et al*., 2014), zero discharge POME treatment (Loh *et al*., 2013a), life cycle assessments (LCA) of palm oil upstream to downstream processes (Choo *et al*., 2011; Subramaniam *et al*., 2010) and building biogas trapping facilities across the country under the Palm Oil National Key Economic Area (NKEA) (PEMANDU, 2010; Loh *et al*., 2014).

While sporadic and extensive research efforts have been devoted towards establishing cost-effective POME treatment technologies, treating POME consistently via biological process is still a complicated subject requiring continued monitoring and improvement. Conventional POME treatment involves ponding system or the so-called waste stabilisation ponds (anaerobic, aerobic and facultative), opened or closed tank digesters, extended aeration and land disposal (DOE, 1999). Through concerted R&D, various technologies and processes have been attempted on POME treatment and so far recorded affirmative and encouraging outcomes, although none has been able to reduce POME BOD to 20 mg litre^{-1} consistently. Among the reported technologies were aerobic digestion via activated sludge reactors, bioreactors inoculated with fungi or bacteria, rotating biological contactors and sequencing batch reactors (SBR); anaerobic digestion via digestion tanks, anaerobic filters (Kobayashi *et al*., 1983), anaerobic fluidised bed reactors (Saravanane and Murthy, 2000), up-flow sludge blanket reactors (Zhang *et al*., 2008; Loh *et al*., 2013a), expanded granular sludge bed reactors and anaerobic baffled reactors; physico-chemical processes such as silent discharge ozoniser (Facta *et al*., 2010), fenton oxidation (Aris *et al*., 2008), electrocoagulation and coagulation; in addition to membrane filtration processes (Idris *et al*., 2010; Loh *et al*., 2013a).

A great number of technologies from the treatability studies, either the laboratory or pilot scale experiments were reported to successfully treat POME to certain convincing degree of removal efficiencies both in the inorganic (nutrients, COD, metals) and organic constituents [BOD, total organic carbon (TOC)]. Oddly, POME treatment still remains challenging in Malaysia and other palm oil producing countries. Most stand-alone technologies were proven efficient in treating POME. However, in actual practice or any full scale IETS, several different technologies are commonly combined to work in stages to further treat and polish the POME to acceptable BOD level. No studies have yet to report on the effectiveness of these stand-alone technologies after technology combination. We hypothesised that they would perform differently in stand-alone and combined treatment line. The combination or arrangement of different technologies into a treatment line would cause altered functioning interface and hence attention is necessary. Besides, previous literatures on POME treatment accentuates on organic pollutant removal. Hence, the present work attempted to monitor several full-scale IETS in POM, identify the efficiencies of stand-alone technologies and compare them after they are combined into series of unit processes with reference to nutrients removal. The effects of pollutant loadings to IETS performance were also investigated. Any technology flaws and influencing factors were identified and discussed to gain insights into POME treatment.

MATERIALS AMD METHODS

In this study, four POM participated for evaluation on the performances of their POME treatment plants. *Figure 1* indicates the location of all four POM. M1's milling activities include crude palm oil extraction, biomass generation, palm kernel processing, fertiliser manufacturing, antioxidant extraction and commercialisation, as well as biogas collection and utilisation. Both M2 and M4 were closely located and approximately within 10 km radius from a water treatment facility. The fact that the mills have close proximity to the water intake point serves as a strong basis on the importance of their polishing plants to produce better quality effluents. Their IETS were installed and upgraded in 2011. Among the POM, M3 was imposed the most stringent discharge limit due to its location directly at the upstream of water intake points. The other three mills were subjected to 100 mg litre^{-1} standard. All four POM TN and AN allowable discharge limit were set at 200 and 100 mg litre^{-1}, respectively.

The IETS installed in all the four POM were identified as a combination of conventional and polishing treatment. The type of technology used in the polishing plants was a criterion for the mill selection in this study. M1's polishing plant represented the suspended growth processes. M2's polishing plant was an attached growth process with moving media/bed while M4's with a fixed bed. M3's on the other hand was a combination of suspended growth processes and physical adsorption. These four polishing plants designs are common in the Malaysian POM. The concerned stages of integrated technologies in each mill were defined as follows, whereby the polishing stages were underlined highlighted.

M1: acidification ponds → closed-tank anaerobic digesters → aerobic pond → SBR→ extended aeration pond → clarifying ponds
M2: anaerobic ponds → algae ponds → suspended packing in activated sludge aeration tanks, with complete mixing
M3: anaerobic ponds → facultative ponds → SBR, followed by clarifier and activated carbon filter
M4: mixing ponds → open tank anaerobic digesters → algae ponds → extended aeration, coupled with fixed packing in activated sludge aeration tank

The collection of POME samples, interviewing the engineers, chemists and IETS handling personnel

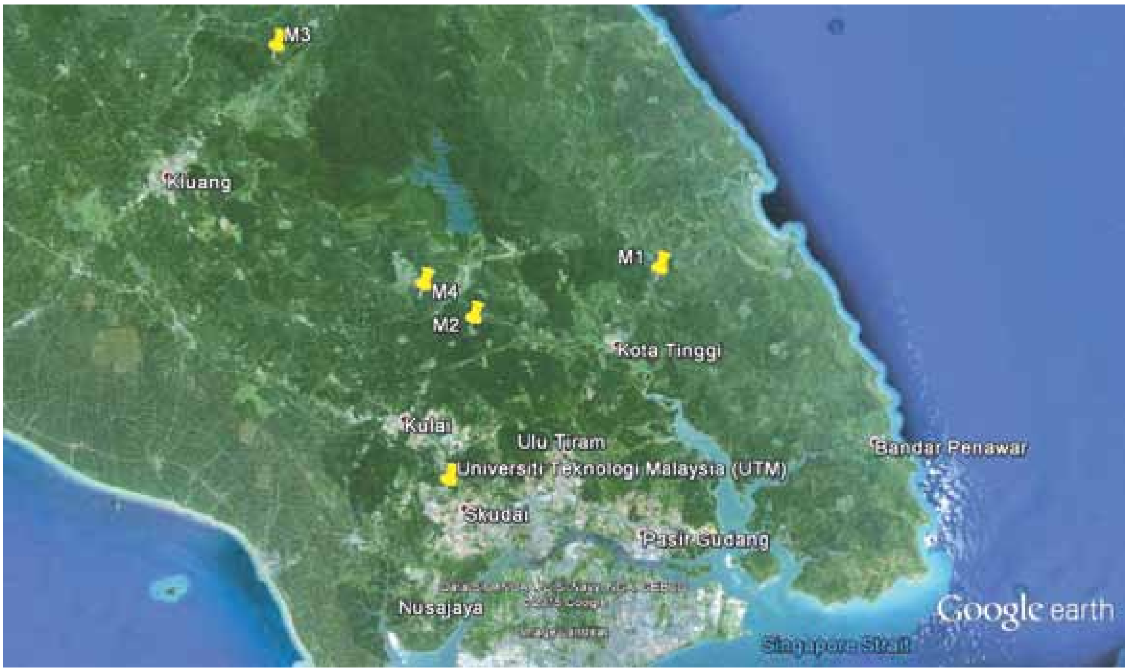

Figure 1. Distribution of the palm oil mills partaken in the study – M1: Kota Tinggi, M2 and M4: Kulaijaya and M3: Kluang.

and on-site inspection were conducted. There were interview sessions in order to understand the milling procedures, operation of the factory and IETS, handling and management of the IETS, performance monitoring of the effluent, sources of water and wastewater throughout the palm oil processing and design of the IETS. Standard operating procedures (SOP) related to the IETS, effluent monitoring reports and laboratory testing results were collected whenever possible. Questionnaires were prepared to obtain information on company profiles, milling capacities and the IETS design information. Some of the information were detailed in *Table 1*. On-site inspections were conducted to gather information on the physical properties of POME (physical conditions, temperature, dissolved oxygen, and pH) at time of sampling events and recorded as in *Table 2*. Sampling events were carried out in three subsequent weeks (three batches) in triplicate using polyethylene containers. All samples were stored at 4ºC in the dark and analysed in the laboratory within 48 hr. POME samples were analysed for the following parameters: BOD (three days, 30ºC), TN, AN and TP based on the standard methods (APHA, 2005). Filtered POME was essential for TN and AN analysis as stated in the regulation (Legal Research Board, 2008), in this case by using the Whatman glass microfibre filter, grade GF/B. The pollutant loads (BOD, TN, and TP) contained in POME were estimated based on per tonne of FFB using the estimation method by Thanh *et al*. (1980). Based on the derived pollutant loads, hydraulic retention time (HRT), removal rates and the collected questionnaires data and documents on the IETS design, the efficacy of the concerned technologies on nutrients removal can be evaluated.

RESULTS AND DISCUSSION

Conventional Ponding System

Commonly, physical and biological processes are combined to remove the organic and readily biodegradable contents in POME derived from the palm oil milling process (DOE, 1999). Raw POME is initially treated in physical pre-treatment steps before entering the secondary biological processes. Among the pre-treatment phases are oil traps or de-oiling tanks, screening and sedimentation. Organic content of POME is treated through a series of ponding systems, which is generally a wastes stabilisation process. This process is a suspended growth biological system which depends on biological cells and requires very long HRT to stabilise the POME. It is also used for settling of sludge or suspended solids (Wong, 1980). Microorganisms like bacteria and algae are primarily involved which result in the production of excess biomass or sludge due to their metabolic activities. De-sludge activities are therefore required to ensure the well functionality of the biological system. Chemical substrates and other physical conditions are required for the biological cells' growth and survival before they ultimately decay (Wong, 1980). Among the types of waste stabilisation ponds (lagoons) in application are maturation ponds, cooling ponds, mixing ponds, acidification ponds, facultative ponds, algae ponds, anaerobic ponds, aerobic ponds and mechanically-assisted oxidation ponds. Facultative ponds typically contain three operational zones, namely the aerobic upper layer, facultative middle layer and the anaerobic sludge layer. Photosynthetic activity of algae pond provides oxygen for aerobic bacteria to perform organic decomposition. Algae pond generally prolongs the facultative treatment period or provides maturation for higher degree of treatment. Ponding system is favoured for its reliable and stable performance, low construction and operation cost, and typically applied in all mills due to land availability. The ponding system can efficiently achieve reasonable degree of BOD reduction *i.e.* 100 mg litre^{-1} (Ma, 1999; Liew *et al*., 2015).

Combined Treatment via IETS

BOD removal. Owing to the complexity of wastewater characteristics, several polishing technologies (*Table 3*) were usually connected in series and combined in an IETS for optimal POME treatment until reaching the targeted discharge limit. The characteristics of the effluent collected from each stage of the POME IETS were described (*Table 3*). Via IETS, the organic constituents were substantially removed. The efficiency of the studied IETS in removing BOD (*Table 4*) was above that studied by Ma (1999), showing BOD reduction exceeded 70% in the ponding systems, as evidenced by M4 achieving 93.5% at the algae ponds, M1 91.0% at the aerobic pond, M2 84.5% at the algae ponds and M3 70.5% at the facultative ponds, respectively before entering the polishing system. Having the most active milling accomplishments in M1, its IETS was a complete combination of several technologies designed to bring down the pollutant loadings to acceptable level. In IETS of M1, effluent leaving the closed-tank anaerobic digesters (33.5% reduction in BOD) entered a series of anaerobic ponds before entering the aerobic pond. Anaerobic pond is normally 7 m in depth to avoid penetration of sunlight and any photosynthetic activity which will introduce oxygen to the system (DOE, 1999). The aerobic pond is mechanically aerated through surface aerator. High BOD reduction performance is expected in the aerobic ponds which ranges between 74% to 81% (Wong, 1980). In the case of M1, the BOD after anaerobic closed tank was further treated to a

TABLE 1. BASIC INFORMATION OF THE PALM OIL MILL EFFLUENT (POME) TREATMENT PLANTS

Information	Palm oil mill (POM)/industrial effluent treatment system (IETS)			
	M1 (1996)*	M2 (1968)*	M3 (2004)*	M4 (1977)*
Average quantities of fresh fruit bunches (FFB) processed per annum (t)[a]	405 146	117 964	235 166	204 142
Estimated quantities of POME generated (t)[b]	271 450	79 040	157 560	136 775
Mill operation (days per annum)	312	348	300	348
Biogas collection facility	Yes	No	Yes	No
Final discharge limit (mg litre^{-1})	100	100	20	100

Note: [a] Calculated based on 13 years of FFB processed data provided by the POM.
[b] Estimated in accordance to the ratio of 0.67 t POME t^{-1} FFB processed (Ma, 1999; Ng *et al*., 2011; Loh *et al*., 2013a).
* Year of operation/commencement.

TABLE 2. SAMPLING LOCATIONS AND WASTEWATER QUALITY CONDITIONS

Location	Condition					
	Unit	Degree of foaming condition[a]	Odour intensity[b]	Temperature[c] (°C)	pH[c]	Dissolved oxygen[c] (mg litre^{-1})
M1						
Acidification ponds	2	*	5	51.5 ± 6.2	5.2 ± 0.2	0.19 ± 0.05
Closed-tank anaerobic digesters	3	Moderate	6	41.0 ± 1.4	6.8 ± 0.4	0.02 ± 0.05
Aerobic pond	1	*	4	27.4 ± 3.2	8.1 ± 0.3	0.81 ± 0.60
Sequencing batch reactors (SBR)	3	Moderate	4	28.6 ± 2.3	8.4 ± 0.2	1.11 ± 0.35
Extended aeration pond	1	Moderate	2	27.9 ± 2.4	8.4 ± 0.2	1.89 ± 0.40
Clarifying ponds	2	Moderate	2	28.4 ± 3.0	8.5 ± 0.3	2.33 ± 0.25
M2						
Anaerobic ponds	4	*	4	27.3 ± 0.6	7.4 ± 0.1	0.41 ± 0.15
Algae ponds	4	Low	2	28.7 ± 0.7	8.9 ± 0.1	1.50 ± 0.60
Suspended packing in activated sludge aeration tanks, with complete mixing	1	High	2	30.4 ± 1.1	8.6 ± 0.3	2.27 ± 0.60
M3						
Anaerobic ponds	2	*	2	34.0 ± 1.4	7.3 ± 0.0	0.25 ± 0.10
Facultative ponds	3	*	2	29.5 ± 0.7	8.8 ± 0.2	1.79 ± 1.20
SBR, followed by clarifier and activated carbon filter	1	*	2	29.1 ± 2.1	8.6 ± 0.2	2.50 ± 1.15
M4						
Mixing ponds	3	Low	5	81.0 ± 13.2	5.3 ± 0.1	0.60 ± 0.45
Open tank anaerobic digesters	9	*	6	32.6 ± 0.8	7.4 ± 0.6	0.07 ± 0.10
Algae ponds	6	High	2	29.2 ± 0.7	8.9 ± 0.1	1.30 ± 0.10
Extended aeration, coupled with fixed packing in activated sludge aeration tank	1	High	2	28.9 ± 0.6	8.7 ± 0.5	3.33 ± 0.90

Note: [a] Degree of foaming condition – from low to high.
[b] Odour intensity description (ranging from 0 = no odour to 6 = extremely strong) according to the Department of Environment, Food and Rural Affairs (2006).
[c] Values are means ± standard deviations (SD) (n = 3).
* No foaming.

TABLE 3. CHARACTERISTICS OF EFFLUENT COLLECTED FROM THE INDUSTRIAL EFFLUENT TREATMENT SYSTEM (IETS)

Location	Parameter[a]			
	BOD (mg litre[1])	TN (mg litre^{-1} NH_3)	TP (mg litre^{-1} PO_4^{3-})	AN (mg litre^{-1} NH_4^+)
M1 (Biogas capture)				
Acidification ponds	4 200 ± 800	395 ± 106	125 ± 21	167 ± 33
Closed-tank anaerobic digesters	2 800 ± 721	268 ± 25	85 ± 50	270 ± 86
Aerobic pond	257 ± 38	275 ± 21	25 ± 21	210 ± 63
Sequencing batch reactors (SBR)	253 ± 46	169 ± 30	25 ± 21	198 ± 75
Extended aeration pond	83 ± 20	51 ± 13	10 ± 0	37 ± 43
Clarifying ponds	83 ± 33	29 ± 10	15 ± 7	19 ± 20
M2				
Anaerobic ponds	807 ± 57	208 ± 13	17 ± 19	281 ± 34
Algae ponds	127 ± 15	124 ± 17	18 ± 4	101 ± 38
Suspended packing in activated sludge aeration tanks, with complete mixing	25 ± 10	14 ± 0.3	14 ± 1	14 ± 5
M3 (Biogas capture)				
Anaerobic ponds	700 ± 212	188 ± 40	38 ± 11	330 ± 65
Facultative ponds	207 ± 142	133 ± 9	32 ± 24	73 ± 21
SBR, followed by clarifier and activated carbon filter	35 ± 18	15 ± 6	14 ± 12	4 ± 3
M4				
Mixing ponds	5 833 ± 1 607	438 ± 12	180 ± 42	139 ± 78
Open tank anaerobic digesters	1 900 ± 1 389	244 ± 9	47 ± 9	264 ± 82
Algae ponds	123 ± 67	115 ± 55	17 ± 2	77 ± 2
Extended aeration, coupled with fixed packing in activated sludge aeration tank	23 ± 6	32 ± 20	12 ± 2	8 ± 3

Note: [a] Values are means ± standard deviations (SD) (n = 3). The BOD, TN, and AN limits for watercourse discharge regulated under the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 are 100, 200 and 150 mg litre^{-1}, respectively.
BOD - biochemical oxygen demand.
TN - total nitrogen.
TP - total phosphorus.
AN - ammoniacal nitrogen.

BOD of 256.7 mg litre^{-1} (*Table 3*) representing 91% efficiency (*Table 4*) at the aerobic pond. Surprisingly, raw POME in IETS of M4 was more efficiently treated anaerobically in open tank digesters (67.5% BOD reduction) compared to POME in M1 (33.5% BOD reduction) and entered the facultative pond before further treated in algae ponds (93.5% BOD reduction) to auxiliary reduce its organic content achieving the highest reduction rate (99.5%, *Table* 5) in BOD amongst the IETS studied.

TN removal. After the aerobic treatment of POME, the highest TN removal was observed in M2 and M3 (89.0%), followed by M4 (72.0%) and M1 (70.0%). The respective combined technologies contributing to this performance were M2: suspended packing in activated sludge aeration tanks with complete mixing, M3: SBR, followed by clarifier and activated carbon filter, M4: extended aeration, coupled with fixed packing in activated sludge aeration tank as well as M1: SBR, followed by extended aeration pond. The common similarities of the combined polishing treatment in the four IETS studied suggested that systems equipped with activated sludge were capable of performing efficient TN removal. Accordingly, the quantity of N removed always represents the quantity required by the suspended biological system (Tchobanoglous *et al*., 2004). This suggested that the operation of these polishing technologies required high nutrients level. Besides, N removal was found occurring at aerobic zone in which biological nitrification took place. This study reinforced the proclamation where all four reported technologies were aerated processes as was evidenced by the presence of complete mixing, SBR and extended aeration. These combined technologies were typically not the final treatment stage for POME as some anoxic volume or time must be allowed for biological denitrification process to complete the objective of N removal (Tchobanoglous *et al*., 2004).

TP removal. Biological P removal occurred at the highest efficiency in M4 (74.0%) and M1 (70.5%).

TABLE 4. EFFICIENCY OF EACH UNIT PROCESS (stage-to-stage) IN AN INDUSTRIAL EFFLUENT TREATMENT SYSTEM (IETS)

Location	Parameter removal rate (%)			
	BOD	TN	TP	AN
M1				
'Acidification ponds' to 'closed-tank anaerobic digesters'	33.5	32.5	32.0	↑ 62.0[a]
'Closed-tank anaerobic digesters' to 'aerobic pond'	91.0	↑ 3.0[a]	70.5	22.0
'Aerobic pond' to 'sequencing batch reactors (SBR)'	1.5	38.5	0.0	5.5
'SBR' to 'extended aeration pond'	67.0	70.0	60.0	81.0
'Extended aeration pond' to 'clarifying ponds'	0.0	43.0	0.0	48.5
M2				
'Anaerobic ponds' to 'algae ponds'	84.5	40.0	↑6.0[a]	64.0
'Algae ponds' to 'suspended packing in activated sludge aeration tanks, with complete mixing'	80.5	89.0	19.0	86.0
M3				
'Anaerobic ponds' to 'facultative ponds'	70.5	29.5	15.5	78.0
'Facultative ponds' to 'SBR, followed by clarifier and activated carbon filter'	83.0	89.0	56.0	95.0
M4				
'Mixing ponds' to 'open tank anaerobic digesters'	67.5	44.5	74.0	↑ 89.5[a]
'Open tank anaerobic digesters' to 'algae ponds'	93.5	53.0	64.5	71.0
'Algae ponds' to 'extended aeration, coupled with fixed packing in activated sludge aeration tank'	81.0	72.0	30.0	89.5

Note: [a] Represents the percentage increase instead of percentage reduction.
BOD - biochemical oxygen demand.
TN - total nitrogen.
TP - total phosphorus.
AN - ammoniacal nitrogen.

Both M4 and M1 were integrated anaerobic treatment processes followed by the conventional ponding system. The similarities observed were presence of anaerobic digesters prior to aerobic or facultative treatment of POME. This treatment circumstance was in agreement with literature detailing the configurations of such removal which involved basic steps of anaerobic zone followed by an aerobic zone (Tchobanoglous *et al*., 2004). Nutrients removal was generally more noticeable in polishing stages of POME treatment although the highest removal did not necessary occur at these stages. TP, however, was seldom reported as the parameter limit for POME discharge regulated under the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977. Despite its considerable advertency, both TN and TP are crucial to ensure the biological systems work well. Inappropriate handling and discharging the improperly treated POME to waterways can contribute to eutrophication or disruption to the industrial water reuse applications.

AN removal. Distribution of AN is a function of pH of the wastewater. Ammonium ion appears principally in raw POME because its pH is below 7. Unlike TN and TP, the level of AN increased in anaerobic digesters, as shown by M1 (↑ 62.0%) and M4 (↑ 89.5%) (*Table 4*). During the anaerobic stages, certain components in POME such as proteins released AN during degradation by biological cells. The AN released (a base) had affinity to combine with carbon dioxide and water to form ammonium bicarbonate which in turn contribute to the increased alkalinity of POME during treatment (McCarty, 1964). Increasing the alkalinity or buffering capacity therefore had resulted in the increase of pH of the acidic raw POME to attain satisfactory treatment. Alternatively, the conversion of organic N in raw POME to ammonia might also intensify AN during anaerobic treatment. Similarly, orthophosphate would also increase for the same cause during waste degradation. This occurrence was necessary for biological growth under anaerobic condition (McCarty, 1964; Kobayashi *et al*., 1983). After anaerobic digestion and further treatment in the respective combined polishing technologies, AN was seen gradually removed with the removal rate in the order of M3 (95.0%) > M4 (89.5%) > M2 (86.0%) > M1 (81.0%). The technologies incurred for AN removal were similar to that in TN removal involving SBR, extended aeration and activated sludge aeration. Other competent AN removal technologies are air stripping, breakpoint chlorination, ion exchange, microfiltration and reverse osmosis (Tchobanoglous *et al*., 2004).

The study opened an argument on the trustworthiness of removal efficiency of stand-alone technologies reported in the literatures. Almost all experimented and investigated technologies on POME treatment claimed high removal rate and suggested their applications for actual IETS in POM. Some of these technologies as shown in this study, however, were noticed to behave differently or even not performing well after combined with other processes. Unfortunately, there is not enough evidence at the moment to show that it is instead the case. Technologies applied to IETS usually perform contrarily compared to laboratory treatability studies and required fine-tuning and continued improvement. For instance, the SBR are known for successful TN, AN and TP removal (Tchobanoglous *et al*., 2004). The situation was true in M3 after combined with facultative treatment, clarifier and activated carbon filter. However, the same technology was not equally performing well in M1 with combination of aerobic digestion and extended aeration. SBR have complex processes design and the effluent quality depends upon reliable decanting facility (Tchobanoglous *et al*., 2004). Therefore, researchers, millers and technology providers should show solicitude for technology combination as the processes integration is sophisticated to achieve optimal POME treatment. Skilled maintenance and operation are other factors contributing to the effectiveness of combined technology implementation in POM.

Overall Performance of IETS

Table 5 shows the overall performance (from anaerobic stage to polishing stage) of the IETS in removal of BOD, TN, TP and AN. The POME quality (organic/nutrient) entering the anaerobic stage was comparable in each IETS *i.e.* BOD (700-2800 ppm), TN (188-267 ppm NH_3), TP (17-85 ppm PO_4^{3-}) and AN (264-330 ppm NH_4^+), thus providing a baseline to justify for a relatively fair comparison of the performance of the four IETS. On top of this, there are many factors affecting the nutrient removal performance of the IETS such as capacity of treatment facility, pollutant loading, treatment mode, age of mill, characteristics of POME, *etc.* As shown in *Table 1*, there were milling similarity in M1, M3 (mill operation, availability of biogas collection, polishing plant designed with suspended growth processes) and M2, M4 (mill operation, no biogas collection facility, polishing plant designed with attached growth processes), respectively except for the milling capacity leading to different volume of POME production. Expectedly, this had led to varying results in their nutrient removal efficiencies. Unfortunately, the results were unable to establish general treatment trend. The decreasing milling capacity and its associated pollutant/organic treatment load were in the order of M1 > M3 = M4 > M2 but surprisingly the corresponding degree of efficiency was M4 = M1 > M3 > M2; thus showed that huge milling capacity and heavy organic load will not necessarily burden the polishing treatment performance if the volume of incoming POME and its organic load were properly managed. In fact, M4 had got the advantage as it was recently upgraded but not the case for M2. It showed the highest overall removal efficiency with BOD 99.5%, TN 92.5%, TP 93.5% and AN 94.5%. However, all of them had yet to comply with the newly regulated BOD 20 mg litre^{-1} during the course of this study. Nevertheless, all of them were able to discharge the effluent according to the parameter limits (100, 200 and 150 mg litre^{-1}, respectively for BOD, TN and AN) regulated under the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977. The polishing technology applied in M4 was essentially an attached growth biological system with fixed

TABLE 5. HYDRAULIC RETENTION TIME (HRT), ESTIMATED POLLUTION LOADS AND OVERALL (anaerobic to polishing) REMOVAL RATES OF THE INDUSTRIAL EFFLUENT TREATMENT SYSTEM (IETS) IN PALM OIL MILLS (POM)

Parameter	Unit	POM/IETS			
		M1	M2	M3	M4
Total HRT	day	180	100	195	60
BOD loads[a]	kg BOD hr^{-1}	2 034.8	531.2	1 228.4	919.2
TN loads[a]	kg TN hr^{-1}	46.8	12.2	28.2	21.1
TP loads[a]	kg TP hr^{-1}	26.6	7.0	16.1	12.0
BOD removal	%	98.0	97.0	95.0	99.5
TN removal	%	92.5	93.5	92.0	92.5
TP removal	%	88.0	14.0	62.5	93.5
AN removal	%	88.5	95.0	99.0	94.5

Note: [a] Estimated based on the average quantity of fresh fruit bunches (FFB) processed per annum (t), mill operation (days per annum) and a ratio of 31.3 kg biological oxygen demand (BOD) t^{-1} FFB; 0.7 kg total nitrogen (TN) t^{-1} FFB; 0.4 kg total phophorus (TP) t^{-1} FFB as described in Thanh *et al*. (1980), and assuming the palm oil processing mills operate 20 hr per day.

bed/media. Biofilm grew and got attached to the specially tailored high surface area plastic media. The carriers were confined in cages in a full scale bioreactor plant suspended with activated sludge. Secondary effluent entered the extended aeration chamber before further treatment in the bioreactor polishing plant. Despite its great performance, the average HRT required to treat POME in M4 was the shortest compared to other IETS. This proposed that shorter time to effectively treat POME was in fact conceivable with correct application and combination of appropriate technologies. Attention needs to be paid on pollutant/organic load as this is a vital design and operating parameter that affects the treatment efficiency and general performance of a biological process (Tchobanoglous *et al*., 2004). Although pollutant/organic treatment load was M1 > M3 > M4 >M2 (*Table 5*), overall high treatment efficiency was evident in these IETS except for TP removal in M2, showing reliable biological treatment systems in use. Generally, biological wastewater treatment systems are capable to handle and tolerate wastes at certain volumetric loading rates and withstand organic shocks without any substantial long-term detrimental effects (Saravanane and Murthy, 2000).

In this case study, M2 was the one with the least performance in nutrients removal especially for TP, most probably due to ineffectiveness in the series of ponding systems, thus insufficient in biodegradation of phosphorus in POME. In fact, discretely, the open/closed-tank anaerobic digesters contributed significantly in organic removal and TP reduction. While the conventional ponding system catered for organic and TP removal, the polishing stage contributed to organic, TN and AN removal. Based on the results, it can be generalised that the IETS having combined polishing system involving either suspended growth or attached growth biological treatment coupled with SBR, clarifier, extended aeration and activated sludge could only consistently remove N containing substrates but not phosphorus. At this point in time, there is not enough data to show the influence among the milling factors in nutrients removal.

Based on current legislative requirement in POME treatment and discharge, the numerous R&D conducted should not just confine to organic destruction to achieve BOD 100 mg litre^{-1} discharge limit, but more ambitious research works should focus on issues at hand *i.e.* to bring down the effluent to a more stringent limit of BOD 20 mg litre^{-1}, colour abatement and sludge reuse. As POME treatment technologies bring down the organic content of effluent, nutrients removal takes place concurrently. Instead of paying devotion to nutrients removal, nutrients recovery is conceivably a more remarkable matter. After treating POME to comply with the discharge standard, the remaining nutrients in effluent or sludge are beneficial for potential applications (Loh *et al*., 2013a, b). In practice, nutrient ratio of the treated effluent is comparable to the nutrient ratio requirement of oil palm, thus provides prospect to utilise the treated effluent as fertiliser supplement by recycling them to oil palm plantations by means of controlled land application techniques (Ma, 1999). Vermicomposting is seemingly a sustainable POME management option to recycle the remaining nutrients in POME as fertiliser. Vermicompost is a nutrient rich product to improve the soil condition in oil palm plantations (Rupani *et al*., 2010). In some mills, anaerobically-treated POME and sludge are applied on empty fruit bunches to accelerate the co-composting treatment. POME sludge is used as nutrient source for the microbial composting treatment as it is high in N, P, potassium (K), calcium (Ca) and magnesium (Mg) (Baharuddin *et al*., 2010; Loh *et al*., 2013a). Although there is already some initiatives focusing on POME nutrient removal and reuse, its value as fertiliser has not outweighed the efforts put in, thus a more holistic approach is required in gearing towards more value addition and a sustainable agriculture in oil palm.

CONCLUSION

In local POM, IETS are merely designed to treat POME to comply with the national discharge limit. Organic and nutrients removal occur simultaneously through different physical and biological processes combined in an IETS treatment plant. In this study, while M4 performed sensibly, the study also highlighted the effectual performance of attached growth biological POME treatment systems. Certain polishing technologies when operated solely in treatability studies performed well but indicated unconvincing results after combined with different polishing components in IETS. Further research is hence required for consensus building in technology applications for integrated POME treatment. On the other hand, nutrients recovery should be highlighted instead of nutrients removal to gear towards cradle-to-cradle waste management approaches.

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