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Investigation on micro-bubble flotation and coagulation for the treatment of anaerobically treated palm oil mill effluent (POME)

P.E. Poh[a,*], W.Y.J. Ong[a], E.V. Lau[b], M.N. Chong[a]

[a] *Chemical Engineering Discipline, School of Engineering, Monash University Malaysia Campus, Jalan Lagoon Selatan, 46150 Bandar Sunway, Selangor, Malaysia*
[b] *Mechanical Engineering Discipline, School of Engineering, Monash University Malaysia Campus, Jalan Lagoon Selatan, 46150 Bandar Sunway, Selangor, Malaysia*

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ABSTRACT

The rapid expansion of the palm oil industry has led to the generation of large volumes of POME in Malaysia. Most conventional aerobic processes for post-treatment of POME are unable to consistently meet environmental discharge standard due to the susceptibility of microorganisms to variable climatic conditions. The main aim of this study was to investigate the potential use of micro-bubbles generated from a venturi tube and the coagulation with polyaluminium chloride (PAC) as a post-treatment method for POME. The micro-bubbles generated from the venturi are capable of removing 57.3% of total suspended solid (TSS) and 74.5% of oil and grease (O&G) and improve the chemical oxygen demand (COD) by 53.7% and biochemical oxygen demand (BOD) by 77.0% with a bubbling time of 12.5 min and a flow rate of 19.8 L/min. However, a single-stage micro-bubble flotation is unable to treat the POME to meet environmental discharge standard. Thus, different PAC coagulant dosage are investigated and the optimum dosage is 2 g/L resulting in at least 93% of COD removal.

Introduction

Palm oil mill effluent (POME) is a wastewater produced from palm oil milling activities and contains high concentration of oil and grease (O&G) and total suspended solids (TSS) with average values of 14,700 and 39,100 mg/L, respectively [1]. Conventionally, several steps of treatment are required to treat POME to meet the environmental discharge standard as stipulated in the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977, involving anaerobic followed by aerobic digestion before discharge to watercourse [2,3].

Before anaerobic digestion (AD), POME is typically de-oiled in an oil trap to recover low-grade oil to gain additional revenue [1]. Nevertheless, the low-grade oil from the de-oiling process should be retained during AD as it could contribute to higher methane production through the digestion of lipids and thus providing higher electricity or steam generation within the palm oil mill in return. With regards to aerobic digestion, the energy requirement for aeration is intensive and the generation of sludge from this process leads to secondary waste disposal problems. Facultative or aerobic post-treatment that uses microorganisms to treat POME is also highly susceptible to environment changes and may not perform consistently. Furthermore, the dark brown coloured substances in POME – derived from molasses melanoidins (MM) generated from the heating of organics from oil extraction process [4] are hardly degraded or decolourized by aerobic and anaerobic activated sludge systems [5,6]. This might create a problem when the treated POME is discharged into watercourses as MM will prevent light from reaching the aquatic plants for effective photosynthesis. Hence, there is a need for a better post-treatment method for POME after AD that can effectively meet the environmental discharge standard.

Conventionally, physico-chemical treatment methods were implemented in primary POME treatment to remove significant amount of suspended solid before passing through membrane modules for filtration [7]. Nevertheless, several studies were conducted on the use of physico-chemical treatment methods (e.g. flocculation, flotation and electroflotation) in the treatment of anaerobically digested POME [8]. It was found that these methods could also effectively remove suspended solids of up to 97%. Furthermore, the application of physico-chemical treatment after anaerobic digestion produced a more consistent quality of treated water regardless of influent variations. These systems are easier to maintain and particulates can be completely removed as well. Out of all the available physico-chemical processes, flotation has a greater potential for the treatment of anaerobically digested POME because this processes has the ability of removing odour, decolourizing the wastewater as well as recovering valuable compounds from the wastewater, which is ineffective when other physico-chemical processes were used [9].

Dissolved air flotation (DAF) is a well-established method commonly used in industries for wastewater treatment mainly to remove oil and suspended solids [10,11]. Typical bubble sizes produced from DAF system are in the order of 100 μm [11]. This DAF method was

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[*] Corresponding author.
E-mail address: poh.phaik.eong@monash.edu (P.E. Poh).

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reported to be able to remove more than 90% of oil and suspended solid (SS) from wastewater with the addition of coagulants [10,12,13]. However, recent researches have shifted to the use of micro-bubbles, with bubble sizes in the order of 10 μm, for wastewater treatment. This is due to the fact that micro-bubbles provide larger contact surface area and have longer residence time, improving the efficiency of oil and SS separation in wastewater treatment [14].

Micro-bubbles can be generated via several methods namely: acoustic cavitation, microfluidic oscillation, porous membranes and hydrodynamic cavitation [14,15]. Although DAF is common in wastewater treatment, the actual DAF system requires high energy to pressurize the air that is to be dissolved in water. In addition, the DAF pressure vessel also requires regular maintenance and inspection [16]. Such technical and operation complexities result in higher maintenance costs for the system. On the other hand, hydrodynamic cavitation generates micro-bubbles through the formation of cavities when liquid flows through a simple geometry such as a venturi tube or orifice plate [14]. The size of micro-bubbles generated through venturi tube can be varied to accommodate the variation in feed flow rate to achieve comparable treatment efficiency of wastewater. However, the use of micro-bubbles generated from venturi tube is yet to be tested as a method for wastewater treatment. The generation of micro-bubbles from venturi tube could potentially replace the conventional DAF systems as the setup for venturi-type micro-bubble generator is simple and does not require construction and maintenance of pressurized vessels.

Though micro-bubbles (generated from DAF) and coagulation are common processes for wastewater treatment, they are mostly employed as a pre-treatment step for POME [15]. In the view that higher oil content should be retained for AD to boost methane production, the use of micro-bubbles generated via venturi tube for anaerobically treated POME should be investigated to evaluate the possibility of replacing aerobic process as a post-treatment method to reduce energy consumption and to produce a discharge that consistently meet the stipulated environmental discharge standards. Furthermore, high volume of coagulant dose is required for anaerobically treated POME to meet the stringent discharge limit imposed by Department of the Environment Malaysia (DOE). The maximum limit imposed by DOE is 50 mg/L for oil and grease, 100 mg/L for BOD and 400 mg/L of TSS.

To the best of our knowledge, studies on bubble size distribution in flotation systems are scarce. In addition, there were no studies that utilize micro-bubble flotation for the separation and recovery of residual oil from anaerobically digested POME. Although precipitate flotation has higher efficiency in the treatment of anaerobically digested POME by destabilizing and aggregating colloids, the potential hazardous voluminous sludge will be the main drawback for commercialization. This study investigates the bubble sizes for its effectiveness as micro-bubbles for the post treatment of POME and also assesses the effect of bubbling time of micro-bubbles on the treatment efficiency of anaerobically treated POME. Furthermore, the optimum dosage of polyaluminium chloride (PAC) to achieve the stipulated environmental discharge standards will be also investigated.

Materials and methods

Anaerobically treated POME

Samples of anaerobically treated POME were obtained from Sime Darby West Oil Mill, located in Carey Island, Selangor. The characteristics of the anaerobically treated POME are listed in Table 1. The samples obtained from the palm oil mill were refrigerated at 4 °C if not immediately used to prevent sample degradation.

Experimental setup

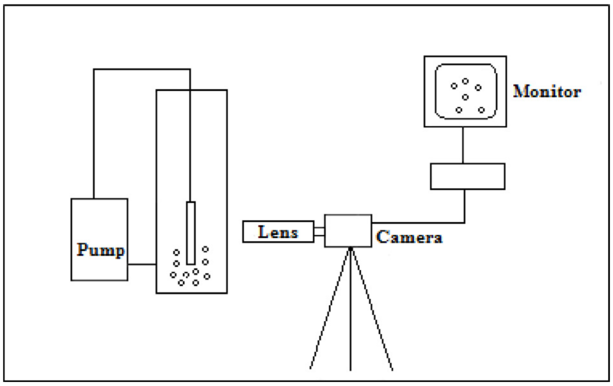

Fig. 1. Setup of the microbubble generation system.

Fig. 1 shows the setup of the micro-bubble generation system, which consists of a 2 L measuring cylinder, a centrifugal pump and an ejector type venturi device which functions to generate micro-bubbles for flotation. The measuring cylinder was filled with 1 L of anaerobically treated POME. When the pump was turned on, the cylinder containing anaerobically treated POME is filled with micro-bubbles that will adhere to the contaminants in POME. The gas holdup of this system is controlled via the flow rate of the water because water determines the volume of air drawn into the throat of the venturi that is eventually broken into micro-bubbles. The bubbles carry the contaminants to the surface of the cylinder forming a layer of foam that is only removed manually using a skimmer after treatment.

The pump was operated at three different water flow rates of 10.2, 19.8 and 26.4 L/min to investigate the effect of water flow rates on bubble sizes and operated under different bubbling times (i.e. 2.5, 5, 10 and 12.5 min) to investigate the effect of bubbling time on the efficiency of contaminant removal. The raw and treated POME samples were analysed in terms of BOD, COD, TSS and O&G in accordance to the standard methods prescribed by the American Public Health Association [17].

Bubble size measurement

Bubble size imaging was done using the charge coupled device (CCD) camera. The images were obtained with the aid of a precision borescope (Brand Hawkeye, U.S. Patent 5,361,166) and a digital camera (QIMAGING RETIGA 200R). The illumination was done using an optic fibre light guide of 50 Hz, 200 W light source (Dolan-Jenner Fibre-Lite MH-100) which was positioned opposite to the camera. The camera was connected to an imaging software (Q-Capture Pro 6.0) to acquire image data from the camera. A sample of the captured image is illustrated in Fig. 2.

Each image captured by the camera contains at least 1 micro-bubble. The micro-bubbles included for size distribution should be positioned in the middle of the image. This is to prevent taking measurements of bubbles from a different plane. Diameters of the micro-bubbles captured with the camera were determined by converting the pixels of the bubbles into the μm scale by comparing with the number of pixels from a reticle scale of 1 mm. A total of 240 micro-bubbles were taken for measurements and the size distributions of the micro-bubbles were plied accordingly.

Jar test

Polyaluminium chloride (PAC) (ACME Chemicals, Malaysia) was used as the coagulant in this study. The PAC used is a fine powder (off-white colour) with 95% min pass through standard 40 mesh (0.42 mm). Coagulation was conducted on the wastewater samples that had undergone bubbling according to methods as described in

Table 1
The characteristics of the anaerobically treated POME.

pH	7.05
Temperature	18
COD	21,025
BOD	2220
TSS	17,995
O&G	235
Electrical conductivity	35.9

All units measured in mg/L except pH, temperature (°C) and electrical conductivity (mS).

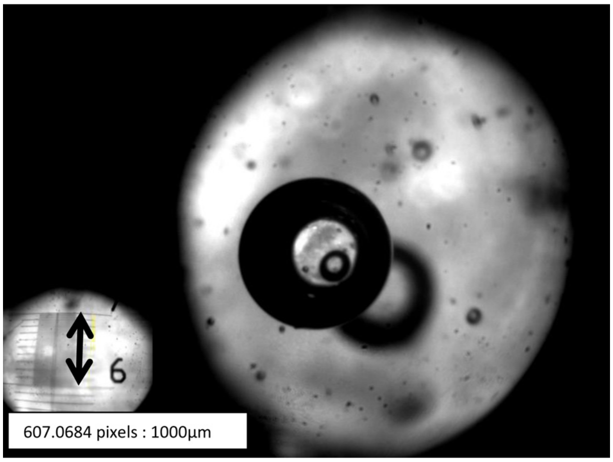

Fig. 2. Images of microbubble captured using charge coupled device (CCD) camera.

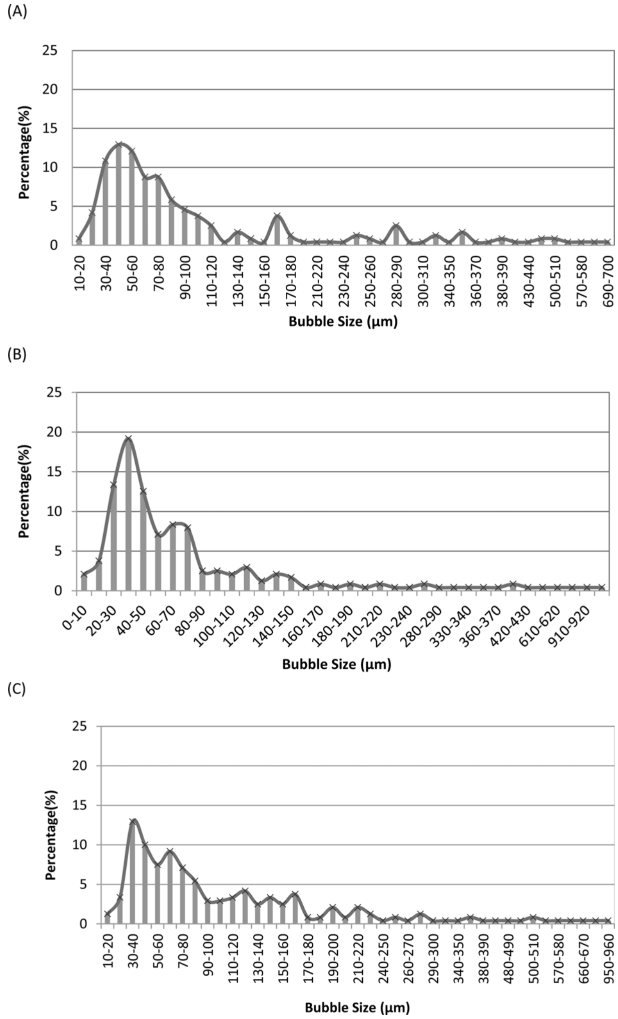

Fig. 3. Plot of size distribution of bubbles at flow rate (A) $Q_L = 10.2$ L/min, (B) $Q_L = 19.8$ L/min and (C) $Q_L = 26.4$ L/min.

'Experimental setup' using a jar apparatus (VELP Scientifica Flocculator, JLT4). Each beaker was filled with 300 mL of POME sample and different dosages of PAC coagulant (0.5–6 g/L) were added and allowed to mix at a constant mixing time of 5 min with a rapid mixing speed of 150 rpm. Subsequently, a low mixing speed of 10 rpm with a steel paddle lifted halfway of the beaker was applied to allow proper formation of flocs. The POME sample was allowed to settle for 30 min and supernatant of the treated POME was then collected for COD and TSS analysis in order to assess the treatment efficiency.

Results and discussion

Bubble size distribution

Fig. 3 shows the size distribution of 240 bubbles captured at three different flow rates of 10.2, 19.8 and 26.4 L/min, respectively. Based on Fig. 3, the size distribution of bubbles produced from the venturi tube became wider when the flow rate was increased. Nevertheless, most of the bubbles had a size range of between 30 and 60 µm, satisfying the requirement to produce micro-bubbles in the order of 300 µm for wastewater treatment [18]. At the lower flow rate of 10.2 L/min, most of the bubbles produced were in the size range of 40–50 µm, constituting 12.9% of the total number of bubbles captured. This is due to the fact that air suction is at a minimum under lower flow rate. Thus, the air vacuumed into the tubular part of the venturi experienced a shock wave and can be efficiently broken into smaller bubbles due to the pressure difference.

As shown in Fig. 3(b), when the flow rate was increased to 19.8 L/min, the predominant size of bubbles was reduced to the range of 30–40 µm (19.2% of total bubbles captured) and the size distribution was narrower thus, showing better consistency in producing bubbles with a smaller size. When the flow rate was further increased to 26.4 L/min as depicted in Fig. 3(c) the size distribution of the bubbles was wider than that obtained under the flow rate of 19.8 L/min. The sizes of the micro-bubbles produced at 26.4 L/min were generally larger and can be in the order of 100 µm. This implies that the flow rates of the water and air entering the venturi have to be investigated prior to any applications to obtain a suitable range of bubble sizes to cater for a particular application.

Micro-bubble flotation of anaerobically treated POME

The micro-bubble flotation of anaerobically treated POME was only conducted at 19.8 and 26.4 L/min due to overheating of pump when operated under a low flow rate (10.2 L/min) for prolonged operating times. In general, the pH of the treated effluent after micro-bubble flotation increased from 7.05 to a range between 7.33 and 8.07 as shown in Table 2. It was found that the degree of increase of pH of the effluent after the treatment increases with prolonged

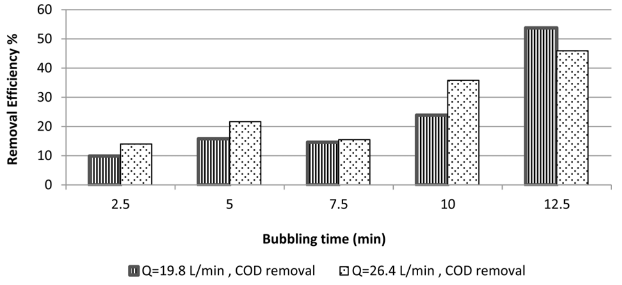

Fig. 4. COD removal of anaerobically treated POME effluent using microbubble of $D_{32} = 469$ and 379.92 µm produced from venturi at flow rate of 19.8 and 26.4 L/min.

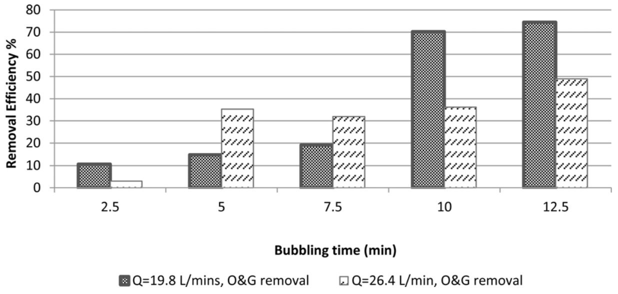

Fig. 5. O&G removal of anaerobically treated POME effluent using microbubble of $D_{32} = 469$ and 379.92 µm produced from venturi at flow rate of 19.8 and 26.4 L/min.

bubbling time at both flow rates. This is due to the dissociation of water molecule into two ionic components hydrogen $[H^+]$ and hydroxyl ions $[OH^-]$ in aqueous solution which neutralized dissolved CO_2 present in medium. Based on Eq. (1), micro-bubble flotation will result in less dissolved CO_2 and forming more bicarbonate species which result with higher pH value [19].

$$CO_{2(gas)} + H_2O \leftrightarrow H_2CO_{3(aq)} \leftrightarrow H^+{}_{(aq)} + HCO_3{}^-{}_{(aq)} \tag{1}$$

A similar trend was observed for the COD removal efficiency as depicted in Fig. 4 where the removal efficiency increased from 9.8% with a 2.5 min bubbling time to 53.7% with a 12.5 min bubbling time at a flow rate of 19.8 L/min while the COD removal efficiency increased from 14.0% with a 2.5 min bubbling time to 45.9% with a 12.5 min bubbling time when operated at a flow rate of 26.4 L/min. The removal of organic matters in wastewater via micro-bubbles occurs either through attachment of suspended matters to the charged surface of micro-bubbles [20] or through oxidation due to collapsing of micro-bubbles which form hydroxyl radicals [12]. However, the COD removal rates through micro-bubble flotation were relatively low as compared to other post-treatment system such as aeration. This is due to the fact that bubbles generated between pH 7–8 have high negative zeta potential [21]. As shown by other investigators [21,22], the zeta-potential distribution of the air bubbles in the absence of surfactants generally has negative zeta-potential. As the pH increases, the negativity increases exponentially. It can be deduced that micro-bubbles having high negatively charged surface could not significantly remove suspended solids at a higher rate due to the COD concentration in the wastewater. The phenomenon could be explained by the electrostatic nature of both bubbles and particles where the electrostatic repulsion will hinder the particles with a negative charge from attaching onto the bubble surface.

Sauter mean diameter (D_{32}) is a measure of surface moment mean diameter. It is normally used in applications where the active surface is important as it is the surface area ratio of the particle of interest. D_{32} can be calculated based on Eq. (2) where d is the diameter of the bubble.

$$D_{32} = \frac{\sum n_1 d_1^3}{\sum n_1 d_1^2} \tag{2}$$

Comparing the micro-bubbles generated at flow rates of 19.8 and 26.4 L/min which has D_{32} of 469.00 and 379.92 µm, respectively in terms of COD removal efficiency, $D_{32} = 379.92$ µm with a smaller diameter showed a higher removal rate for bubbling times from 2.5 to 10 min. This is due to the fact that smaller bubbles accelerate the formation of hydroxyl radicals due to higher inner pressure which is able to cleavage the conjugated carbon-carbon double bonds for MM which are responsible for the brown colouration in POME. It was demonstrated by Liu et al. [12] that the presence of hydroxyl radicals contributes to the degradation of the organic component in dye and coke wastewater. Furthermore, smaller bubbles with larger surface area improve the bubble-to-particles' collision efficiency, yielding higher COD removal efficiency in the system at shorter bubbling periods.

However, when the bubbling time was prolonged to 12.5 min, the micro-bubbles with $D_{32} = 469.00$ µm showed better removal efficiency with maximum COD reduction of 53.7%. In the process of micro-bubble flotation, the micro-bubbles that float to the surface of the liquid were observed to form a layer of foam that cannot be broken easily when the wastewater was recirculated. The foam layer develops faster at a higher flow rate and thickens with increased bubbling time. Due to foaming, the water level in the column decreases leading to a shorter distance being available for the bubble to travel. When the micro-bubble generating system was operated at 26.4 L/min for 12.5 min, the thicker layer of foam resulted in less displacement for the micro-bubbles to travel. Subsequently, this reduces the contact of micro-bubbles with contaminants in the anaerobically treated POME resulting in lower COD removal than in the case of larger bubbles.

Based on Fig. 5, the capability of removing O&G from the anaerobically treated POME increased with bubbling time. This is attributed to the rise in temperature from pump friction and cavitation during the operation. The degree of temperature elevation increases with bubbling time. The temperature of the system increased from 18 to 26 °C during the period of bubbling. Furthermore, the rise in pH due to prolonged bubbling, contributed to the dissociation of OH^- ions from the wastewater causing the OH^- ions to undergo saponification with residual oil thus, producing soap which is water soluble and resulting in high removal rates at longer bubbling time [23]. It was also found that at a pH greater than 7, oil molecules exhibit high affinity on negatively charge surfaces to form a negatively charged particle [24]. Therefore, the adsorption of oil particles will be more favourable as the bubbling time increases.

The O&G removal capability was more pronounced when the micro-bubble generation system produced micro-bubbles with a larger $D_{32} = 469.00$ µm at a flow rate of 19.8 L/min. The smaller bubbles with larger surface areas generated under the flow rate of 26.4 L/min did not perform as well as the larger micro-bubbles if the treatment time is prolonged. The smaller-sized micro-bubbles did not remove as much O&G because of their smaller rising velocity [25] which takes predominance over the total surface area as the determining factor of removal efficiency over total surface area. Due to the fact that the O&G particles have long carbon chains, hence high molecular masses [26], the larger micro-bubbles with larger rising efficiency are able to float and remove the heavy oil particles more effectively [14].

Fig. 6 depicts the BOD removal efficiency at different bubbling times. The results indicated better removal efficiencies at longer bubbling times and a higher BOD removal efficiency can be achieved when the system is operated at a flow rate of 19.8 L/min which produces micro-bubbles with larger SMD. The highest achievable BOD removal

Table 2
pH and electrical conductivity of the effluent at different bubbling times.

Bubbling time	Initial pH 7.05		Initial electrical conductivity 35.9 mS	
	Final pH		Final electrical conductivity	
	$Q_L = 19.8$ L/min	$Q_L = 26.4$ L/min	$Q_L = 19.8$ L/min	$Q_L = 26.4$ L/min
2.5	7.42	7.33	–	23.12
5	7.68	7.71	–	16.41
7.5	7.88	7.69	–	22.60
10	8.00	7.94	–	14.30
12.5	8.06	8.07	–	12.51

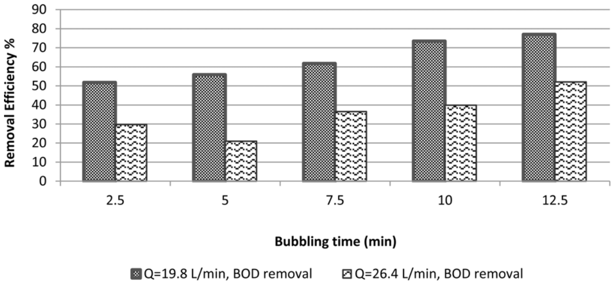

Fig. 6. BOD removal of anaerobically treated POME effluent using microbubble of $D_{32} = 469$ and 379.92 μm produced from venturi at flow rate of 19.8 and 26.4 L/min.

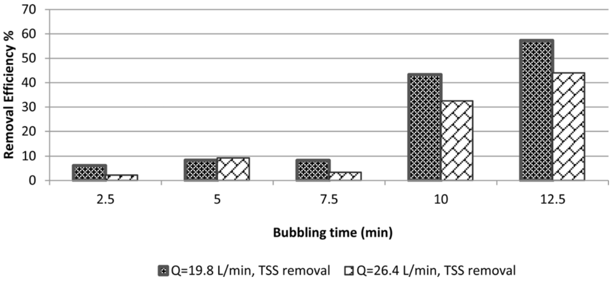

Fig. 7. TSS removal of anaerobically treated POME effluent using microbubble of $D_{32} = 469$ and 379.92 μm produced from venturi at flow rate of 19.8 and 26.4 L/min.

efficiency at 19.8 L/min was 77% at 12.5 min bubbling period. Normally, smaller micro-bubbles with a greater total surface area will contribute to greater flotation efficiency of particles in the same fluid body due to high mass transfer flux [14,27]. Nevertheless, the converse was observed based on the results from BOD analysis, where the smaller micro-bubbles (26.4 L/min) achieved lower removal efficiency, with only 52% of BOD removed.

Hence, it is postulated that the effect of surface area on the removal efficiency was outweighed by the effect of the rising velocity where the smaller bubble size may be able to attract more particles, but the overly low rising velocity causes fewer bubbles to reach the surface in the given time frame leading to a lower removal rate. This effect is particularly pronounced due to the large masses of complex organic particles, leading to an even lower rising velocity and BOD removal rate.

As seen in the results, bubbling treatment achieved a greater BOD removal than COD removal indicating that bubbling flotation treatment is more effective in removing bio-organic particles than the inorganic particles. The bio-organic particles in POME such as complex lipids, carbohydrates and cellulose, are generally much larger in terms of molecular volume than inorganic particles such as potassium and sodium ions. The micro-bubbles were likely to be more effective in floating large particles than smaller ones as the small inorganic particles have volumes that are many magnitudes smaller than that of the micro-bubbles and thus, experienced a streamline ‘sliding’ effect, sliding off the surface of the micro-bubbles [28].

From Table 2, the electrical conductivity of the supernatant level was found to decrease with bubbling time. This indicates the decrease in concentration of charge carriers at the supernatant level at the end of bubbling. The charge carriers present in POME are small inorganic ions such as Na^+, K^+, Zn^{2+}, and complex ionic organic molecules [29]. A decrease in electrical conductivity implies that ions have been removed from the solution. Based on a study conducted by Rodrigues and Rubio [30], it was found that flotation was inefficient when particles are smaller than 13 μm. Furthermore, the collection mechanism should form a finite contact angle at the gas–liquid–solid interface which enables efficient bubbles and particles collision causing adhesion on the surface of the bubbles. When bubbling time was conducted at 12.5 min, the decrease in conductivity was about two-thirds of the original value. Such a significant decrease in the conductivity is unlikely to have stemmed from the removal of only small amounts of inorganic ions; the great removal of ionic organic molecules is likely to have contributed more to this decrease in conductivity from the bubbling. This has proven that COD and BOD removal are unlikely to be greatly contributed by ions contained in POME when larger bio-organic particles is being floated up to the surface [31,32].

It is shown from Fig. 7 that though the TSS removal efficiency increased with bubbling time, the effect of TSS removal was not apparent with short bubbling periods. It was found that the highest TSS removal efficiencies were obtained at a bubbling time of 12.5 min at a flow rate of 19.8 and 26.4 L/min, respectively. The efficiency of the system to remove TSS was more pronounced with prolonged bubbling time due to the fact that more micro-bubbles were produced with longer bubbling period. Physical contact between the bubble surfaces at high bubble density in POME will cause the uncharged carbon chains of the organic molecules to attach onto the surface of the bubbles and subsequently floated up to the surface of the liquid. The main mechanisms involved for the bubbles to float up particles and impurities are through physically entrapment within the particles in POME or through nucleation or aggregation at the surface [30]. However, the smaller bubbles generated at the flow rate of 26.4 L/min (larger surface area) did not perform as expected due to foaming issue as mentioned earlier. The displacement of water level highly reduces the probability of collision of particles with the bubble surface thus, leading to reduced suspended solids removal.

A previous study by Tuan et al. [33] claimed that micro-bubbles alone cannot carry out the removal of contaminants efficiently and often the use of coagulant is the predominant factor that reduces the colloids in the wastewater. Theoretically, most wastewaters are negatively charged and require coagulants to neutralize the negatively charged particles for better removal via DAF. However, it was observed from this study that the experimental results only agreed with the aforementioned statement for bubbling time up to 7.5 min. When the bubbling time was increased to 10 and 12.5 min, the results did not concur with literature findings, showing significant amount of removal of contaminants. Due to the lack of research conducted on the removal of contaminants in the wastewater using micro-bubbles

Table 3
Final effluent characteristics after anaerobic digestion, microbubble flotation and coagulation (MB flotation flowrate = 19.8 L/min, bubbling time = 12.5 min) and DOE discharge limits.

	Anaerobically digested POME (ADPOME)	Effluent after micro-bubble flotation (19.8 L/min)	Effluent after micro-bubble flotation (26.4 L/min)	Effluent after micro-bubble flotation (19.8 L/min) + PAC coagulation	DOE discharge standard
pH	7.05	8.06	8.07	6.28	5–9
Temperature	18	26	27	25	45
COD	21,025	9725	11,375	1407	–
BOD	2220	510	1065	Not detected	100
TSS	17,995	7685	10,080	22	–
O&G	235	60	120	Not detected	50

All units measured in mg/L except pH and temperature (°C).

alone, there is no available benchmark to compare this off-trend observation. It is expected that for bubbling times of 7.5 min and below, the electrostatic repulsion between the surface negative charge of the bubbles and the negatively-charged groups of the organic molecules in the POME prevents the micro-bubbles to function effectively as an attractive vessel for the molecules to attach. However, when the bubbling time was increased beyond 10 min, the high bubble density in the POME increases the chance of physical contact between the bubble surface and the uncharged carbon chains of the organic molecules. In this case, the repulsion between the negative groups may not be strong enough to repel the molecules off the surface of bubble as the high bubble density means that the gaps between the bubbles will be smaller. Furthermore, as bubbling time is prolonged, the temperature of the setup will increase due to pump cavitation and also pump friction. At higher temperatures, the zeta potential of the micro-bubble surfaces will be less negative. The electrostatic repulsive force between the bubbles and organic molecules will be weaker as negative charge on the bubble surface will be weaker thus, improving the attachment of contaminants on the micro-bubbles.

Although significant removal of contaminant was obtained with the use of micro-bubble flotation, the effluent produced still does not meet the DOE discharge limits. As a result, further treatment using a chemical to remove impurities was required in order to meet DOE discharge standards.

Coagulation of effluent after micro-bubble flotation

PAC coagulant was added to further reduce the strength of POME after micro-bubble flotation and the optimum dosage of PAC required to meet the DOE discharge standards consistently was investigated in this study. Coagulation was not conducted before micro-bubble flotation in this study as it is anticipated that the surface area of the micro-bubbles will form hydrophobic interaction with the neither organic compound nor lipids in POME to separate and recover oil-in-water emulsion in POME. Under suitable condition, micro-bubble can remove organic compound or O&G in a non-selective manner without addition of any other chemicals. Thus, the oil can be further recovered for other uses and less coagulant is needed to treat the effluent if micro-bubble flotation is employed prior to coagulation. Based on Figs. 8 and 9, the optimum dosage for appropriate TSS and COD removal was 2 g/L. The results obtained was in concurrent with the findings by Duan and Gregory [34] where 2 g/L of PAC was found to be the optimum dosage and any further increase in the coagulant dose was only to yield a slightly higher TSS removal. Higher dosage will enhance the removal of TSS and COD in POME due to the emitting of more polyhydroxides and greater electrical charge will be in contact with the colloidal particles in the solution, resulting in the formation of flocs [35]. However, additional dosage will cause the particles to restabilize due to surface saturation, thus showing insignificant removal for TSS [36].

Even without the coagulants, there was significant COD removal due to the settling of denser suspended solids in the effluent after micro-bubble flotation as shown in Fig. 9 (PAC dose at 0 g/L). Based on Fig. 8, the samples from 2.5 and 5 min micro-bubble flotation have higher COD removal efficiency prior to dosing of coagulants due to the denser suspended solids removal through physical contact with the micro-bubbles produced earlier in the experiment. This left to less dense suspended organic and inorganic components in the wastewater.

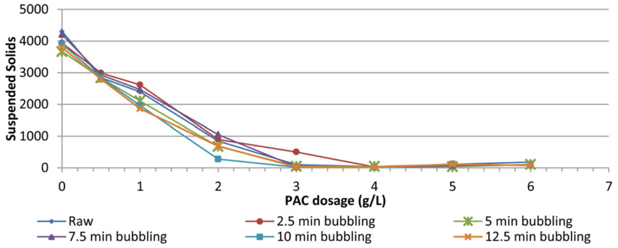

Fig. 8. TSS value of treated POME at various coagulant dosage.

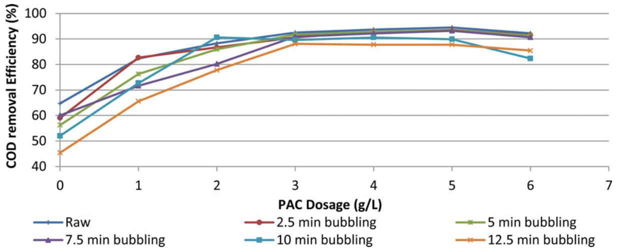

Fig. 9. COD removal of treated POME at various coagulant dosage.

The COD removal showed a similar trend to suspended solids removal as the coagulant dose increased. As shown in Fig. 9, for a longer bubbling time (7.5, 10 and 12.5 min bubbling time) POME showed slightly lower removal when compared to the shorter bubbling POME (raw, 2.5 and 5 min bubbling time). This is due to the fact that a significant amount of organic and inorganic substances were removed during micro-bubbles treatment. Micro-bubbles were likely more effective in floating the large particles, while the remaining smaller inorganic particles have volumes that are much smaller and cannot be settled through gravity thus, required an optimum coagulant to agglomerate into bigger flocs to enhanced settling.

Fig. 10 shows the overall COD removal efficiency of the anaerobically treated POME after micro-bubble treatment and PAC coagulation. Based on Fig. 10, the contribution of micro-bubble treatment on the removal of COD from anaerobically treated POME was very minimal where most of the COD were removed through the addition of the coagulant. However, the application of micro-bubbles prior to the coagulation did aid the coagulation process as the bubbles remaining in the system aided to bring the colloids into suspension.

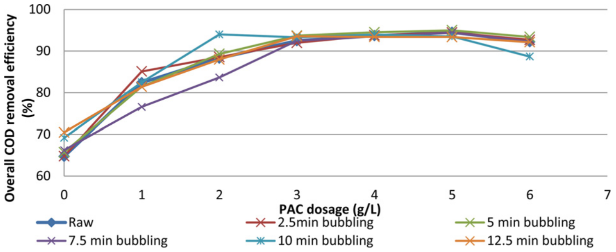

Fig. 10. Overall COD removal efficiency for treated POME at various coagulant dose.

This was evident after the addition of coagulant, where air bubbles were found trapped in between the colloids when the colloids floated up to the surface of the treated effluent. The removal of suspension from the treated effluent will be less complicated when treatment is conducted at a larger scale as a skimmer can be used to remove the floating suspension.

Table 3 shows the effluent characteristics before micro-bubble flotation, after micro-bubble flotation and after micro-bubble flotation with PAC coagulation. These characteristics were compared against the DOE discharge standards for POME. Based on Table 3, though micro-bubble flotation significantly removed contaminants from the anaerobically treated POME, most parameters (except pH and temperature) does not conform to DOE discharge standards. The quality of the effluent improved and adhered to the discharge standards after subsequent treatment with PAC coagulation. In conclusion, micro-bubble flotation should be coupled with coagulation to produce effluent that meets the discharge standards of DOE. Further work should be conducted to evaluate the social, environmental and economic impact of replacing aerobic treatment with micro-bubble flotation and coagulation into existing POME treatment system to improve the sustainability of palm oil milling process.

Conclusion

- Based on the results obtained in this study, it was found that the micro-bubble flotation treatment efficiency increases with bubbling time.
- The maximum performance attainable from the applied system was at a fluorite of 19.8 L/min removing 53.7% of COD, 57.3% of TSS, 74.5% of O&G and 77.0% of BOD.
- The low removal efficiency of the micro-bubble flotation treatment indicates that surface charge of the bubbles does not favour the particles in POME to be adsorbed onto the surface for floatation. Therefore, a coagulant is required after micro-bubble flotation to produce effluent that meets the environmental discharge standards.
- It was found that the optimum dosage of the PAC coagulant was 2 g/L for the effluent from micro-bubble flotation.

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