Performance and Stability of Pre-commercialized Integrated Anaerobic–Aerobic Bioreactor (IAAB) for the Treatment of Palm Oil Mill Effluent (POME)

Yi Jing Chan, Roy Jun Wei Chong, Mei Fong Chong, Denny Kok Sum Ng, and Lian Keong Lim

Abstract This chapter aims to evaluate the performance of a pre-commercialized Integrated Anaerobic–Aerobic Bioreactor (IAAB) (3000 m^3) under variable organic loadings and environmental conditions with respect to effluent quality and methane yield. During the steady state operation of IAAB, the system achieved 99% of removal efficiency for Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD) and methane yield up to 0.26 L CH_4/g COD at organic loading rate (OLR) of 2.0–20.0 g COD/L day. Achievement of BOD <100 mg/L throughout 200 operational days with 45% of compliance was reported. The system could significantly reduce 70% of footprint and 78% of hydraulic retention times compared with current conventional treatment systems (e.g., cover lagoon, anaerobic bioreactor, etc.). During the operation, there are number of issues such as scum formation and foaming in the system. By manipulating the sludge recirculation rate within the range of 70–140 m^3/h, the scum and foaming issues are resolved in anaerobic compartment. Meanwhile, the foaming issues in aerobic compartment were successfully resolved by dosing the advanced biological formulation produced by Novozymes, namely Bioremove 5100 and Bioremove 3200 at optimum ratio of 50:50. Further work on optimization for the recirculation flow rate in the anaerobic compartment with consideration of fluid dynamics and microbiology is required to achieve 100% compliance of BOD <100 mg/L.

Y. J. Chan (✉) · R. J. W. Chong
Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
e-mail: Yi-Jing.Chan@nottingham.edu.my

M. F. Chong
628, Jalan Pulau Tioman U10/94, 40170 Taman Greenhill, Shah Alam, Selangor, Malaysia

D. K. S. Ng
School of Engineering and Physical Sciences, Heriot-Watt University Malaysia, Putrajaya, Malaysia

L. K. Lim
Havys Oil Mill Sdn Bhd, C/O Paramount Estate, KM31 Jalan Bahau-Keratang, Mukim Bera, Pahang Darul Makmur, Malaysia

D. C. Y. Foo et al. (eds.), *Sustainable Technologies for the Oil Palm Industry*,
https://doi.org/10.1007/978-981-19-4847-3_12

Keywords Palm oil mill effluent (POME) · Anaerobic · Aerobic · Integrated anaerobic–aerobic bioreactor (IAAB) · Biogas · Methane yield

Nomenclature

Abbreviation

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
MLSS	Mixed Liquor Suspended Solid
MLVSS	Mixed Liquor Volatile Suspended Solid
RAS	Returned activated sludge
OLR	Organic Loading Rate
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
UASFF	Upflow Anaerobic Sludge Blanket Fixed Film
POME	Palm Oil Mill Effluent

1 Introduction

Malaysia has been experiencing a rise in economic growth as it is one of the largest contributors in palm oil products worldwide. The massive growth of oil palm tree is blessed by Malaysia's tropical climate that facilitates these successful agricultural schemes. Lately, Malaysia contributed 33% of world exports and 28% of world palm oil production (MPOC, 2020). However, the production of crude palm oil (CPO) has also generated significant amount of wastewater, namely palm oil mill effluent (POME). POME is recognized as an agro-output that exhibits high acidity with average values of 50,000 mg/L chemical oxygen demand (COD) and 25,000 mg/L biochemical oxygen demand (BOD) (Yacob et al., 2005). Fresh fruit bunches (FFBs) harvested from oil palm plantation are sent to the palm oil mill for extraction of CPO. Then, CPO is further purified in refinery to be palm oil products (e.g., styrene, soap noodle, etc.). POME are generated during the steam condensate during the sterilization process, decanter, etc. Such waste is required for proper treatment prior discharging into the environment. It was reported that most palm oil mills in Malaysia operate at a capacity of 45 t/h of FFB which produces 29.25 t/h POME (Akhbari et al., 2020). Undoubtedly, this has triggered the need for better agricultural, industrial, and sustainability practices to be implemented in palm oil mills to combat the depletion in environmental quality posed by this industry.

Generally, POME treatment involves both anaerobic and aerobic degradation, as applying former method alone is insufficient to meet the current effluent discharge legislation. Chan et al. (2009) has reviewed that the organic matter in anaerobic effluent are not completely stabilized and an additional post treatment step is required to treat the ammonium ion and hydrogen sulfide found in effluent (Chan et al., 2009). Anaerobic digestion is proven to render low energy cost, reactor volume, high organic load treatment while producing biogas for energy supply; however, further polishing of POME effluent is required (Tchobanoglous et al., 2004). Hence, aerobic degradation is implemented to further treat the anaerobic effluent to meet the stringent discharge standard. Moreover, the anaerobic–aerobic process is capable of providing higher overall treatment efficiency, while effectively reducing energy consumption, as well as sludge disposal (Cervantes et al., 2006; Frostell, 1983). The anaerobic–aerobic system using high rate bioreactors have been extensively studied to identify better options in treating POME. For instance, the *upflow anaerobic sludge blanket* (UASB) reactor has demonstrated various positive features such as its capability in treating high organic loadings with short hydraulic retention time (HRT) while consuming less energy (Tchobanoglous et al., 2004).

Since then, various novel designs which incorporate the features of UASB have been proposed to enhance bioreactor performance in treating POME. Najafpour et al. suggested to couple upflow fixed film (UFF) with a UASB reactor to shorten the start-up period at low HRT. The hybrid reactor, i.e. upflow anaerobic sludge-fixed film (UASFF) bioreactor was proven to be able to remove 97% COD at HRT of 3 days with organic loading rate (OLR) of 11.58 kg COD/m^3 day Najafpour et al. (2006). Poh and Chong (2014) also demonstrated that an upflow anaerobic sludge blanket-hollow centered packed bed (UASB-HCPB) reactor could remove 90% COD and BOD, and 80% suspended solid, while producing 60% methane (Poh & Chong, 2014). Nonetheless, these high-rate bioreactors are still in their infancy in term of up-scaling due to high cost and unstable performance.

In recent years, the idea of utilizing a compact high-rate bioreactors has garnered attentions in overcoming space limitations, odor problems and biosolids production (Chan et al., 2009). The high rate integrated anaerobic–aerobic bioreactors (IAAB) have been developed to replace the conventional treatment methods mentioned above. IAAB can be defined as a breakthrough in innovation as it exploits both benefits of both the anaerobic and aerobic degradation processes while providing better biodegradation. The capability of IAAB in treating POME within a short hydraulic retention time at reduced space utility has been demonstrated at previous study. The overall COD, BOD, and total suspended solids (TSS) removal efficiencies greater than 99% were attained for OLR up to 18.5 g COD/L day with methane yield of 0.32 L CH_4/g $COD_{removed}$ (Chan et al., 2012). Prior to industrial application and commercial adoption, basic knowledge and technological advancement ought to be conducted via pilot or demonstration plants. In addition, the initiative of pilot plants is subjected to create a balance between establishing technologies and constructing a first commercial market. Previous pilot studies on IAAB have shown to exhibit good stability, high performance in terms of POME substrate removal efficiency >99% and methane yield of 0.24 L CH_4/g COD removed with OLR of 10.5 g COD/L day as compared to conventional system (Chan et al., 2012). Similarly, evaluation of biokinetic coefficient on IAAB suggested that OLR range of 10.5–22.5 g COD/L day results in POME substrate removal > 99% while producing up till 64% of CH_4 gas (Chan et al., 2017). The study has shown encouraging results and hence, the current study focuses on utilizing the similar IAAB design at a pre-commercialized scale to further evaluate the efficiency of the unit in treating POME. The aforementioned studies are deemed successful and promising, yet only applicable in pilot scale applications. Hence, the present study was undertaken to investigate the performance of the pre-commercialized scale IAAB at different OLRs under mesophilic condition. The determined maximum sustainable OLR will indicate whether the proposed novel design is practical for industrial utilization. In addition, the study on the effect of mixed liquor suspended solids (MLSS) and F/M ratio are of great importance as it will affect the overall performance of IAAB if not taken into appropriate measurements. Furthermore, poor mixing behavior has shown to impose large positive impact in the digestion efficiency when considering up-scaling of IAAB, since most commercial digester inhibit continuous mixing process (Kobayashi et al., 2013). Thereafter, operational issues encountered by pre-commercialized IAAB such as foaming in aerobic compartment and scum formation in anaerobic compartment will be emphasized. The current study provides the recommended operating conditions of OLR, MLSS, and F/M ratio which give the highest methane yield, total removal efficiency of COD and BOD while mitigating operational issues faced by pre-commercialized IAAB, thus to maintain high performance and stability for the long run. This work is significant as these development activities are not only addressing pure technical challenges, but also reducing the organizational, market, and institutional risks and uncertainties that key stake-holders might face in this advancing new technology i.e. IAAB.

2 Materials and Methods

2.1 Wastewater Preparation

In this project, the pre-commercialized IAAB is built at a palm oil mill located in Pahang, Malaysia. Therefore, the POME is taken directly from the palm oil mill. Over the period, the characteristics of the POME are evaluated and presented in Table 1.

2.2 Reactor Configuration and Operating Procedures

The pre-commercialized IAAB is built to treat the raw POME based on IAAB system. The simplified process flowsheet is shown in Fig. 1, while the photo for the unit is

Table 1 Characteristics of POME

Parameter	Units	Average	Range
pH	–	4.5 ± 0.10	4.18–4.7
BOD	mg/L	35,100 ± 10,391	4100–86,700
COD	mg/L	74,016 ± 37,738	8500–176,400
TSS	mg/L	31,611 ± 15,531	31,200–34,300

shown in Fig. 2. This IAAB unit has a design capacity of 10 m^3/h (maximum inlet flowrate) which is about 20% of the full-scale plant based on a 60 t/h of FFB mill capacity. As shown in Fig. 1, the IAAB system consisted of a transfer sump, IAAB unit, treated effluent tank, and sludge holding tank.

Raw POME is fed to the transfer sump where a grip trap with bar screens are installed to filter out coarse solids and debris. The raw POME is stored in transfer sump to ensure a constant supply of POME into the anaerobic compartment, in which the degradation of complex organic matter without oxygen occurs. The feeding system is designed in an upflow manner and the POME is fed into a liquid distribution system through an inverter controlled feed pump. This anaerobic compartment with an effective volume of 1125 m^3 is the major equipment in the biogas plant. The anaerobic compartment is inoculated with the anaerobic sludge obtained from the ponding system in the same palm oil mill. The anaerobic bacteria activity, MLSS, pH profile and upflow velocity were maintained for an efficient performance. Recirculation system is introduced in the anaerobic compartment to ensure homogenous and uniform distribution of the POME. For the purpose of sampling and the removal of scum, POME can be released from the side of the anaerobic compartment to the

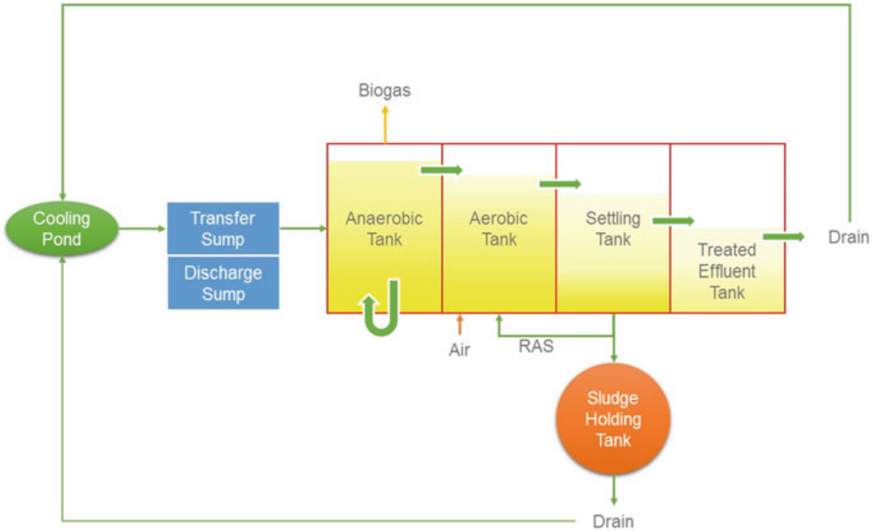


Fig. 1 The simplified IAAB system for the treatment for POME (Chan et al., 2020)

Fig. 2 Pre-commercialized scale of IAAB system (*Courtesy of* Havys Oil Mill Sdn. Bhd.) (Chan et al., 2020)

drain sump. Biogas was collected from the geo-membrane installed at the top of the anaerobic compartment (Fig. 2) and be sent to a moisture separator (MS) for moisture removal. A flame separator (FS) is also used to prevent fires or explosions before releasing the biogas from the blower at 40 °C and 1 atm. The pressure of the biogas in the geo-membrane was controlled by using blowers at 0.4 mbar. The safety of the biogas geo-membrane was ensured with manual relief valve. After being treated anaerobically, POME overflows into the aerobic compartment (977 m^3) where the waste is further digested in the presence of oxygen. Blower is used to supply air from the surroundings with a dissolved oxygen (DO) concentration of 3 ppm to the aerobic compartment. This is mainly to allow complete sludge mixture in the reactor and to supply adequate dissolved oxygen for biological processes.

From aerobic compartment, the POME overflows into the settling tank where the sedimentation process occurs, allowing the sludge to settle by gravity. The sludge is then transferred to the returned activated sludge (RAS) pump system, where a portion of the solids is returned to the aerobic compartment to maintain the desired biomass concentration in the aerobic compartment. The remaining portion of the sludge is transferred to a sludge holding tank where the sludge is kept in storage. The sludge can either be pumped into the effluent overflow drain by the sludge pumps or be transferred to the transfer sump. Finally, the treated POME flows into the treatment effluent tank from settling tank and is discharged as clear water.

The treatment performance of the IAAB system was monitored and analyzed. The stability of the reactor was assessed in terms of pH, MLSS concentration, and food-to-microorganism (F/M) ratio. Samples were collected at different sampling points along the anaerobic and aerobic compartments. The achievement of more than 65% of COD removal efficiency for three consecutive days was taken as stable performance of the IAAB.

2.3 *Analytical Methods*

For anaerobic process, several monitoring parameters were evaluated during the entire operation, including COD, BOD, and TSS concentrations of the effluent, as well as pH, temperature, $MLSS_{an}$, of the anaerobic compartment together with methane yield and methane composition. Whereas for aerobic process, the COD, BOD, TSS concentrations, and pH of the treated effluent, as well as temperature, DO, and $MLSS_a$ of the aerobic compartment were analyzed. Analytical determinations of BOD, COD, and TSS were carried out in accordance with the Standard Methods for the Examination of Water and Wastewater (Association et al., 1912). BOD_3 was analyzed on samples incubated for 3 days at 30 °C according to the EQA 1974. COD was analyzed by using the colorimetric method with a HACH spectrophotometer (DR2000, Loveland, CO). TSS and MLSS was determined by filtering a sample through a glass fiber filter (Whatman grade GF/A, 1.6 μm, UK) and the residue retained on the filter is dried in an oven (Memmert, Germany) at 105 °C whereas VSS and MLVSS were determined by ashing the dry sample in a 550 °C muffled furnace (Carbolite, UK) for 15 min. The composition of biogas was measured using a biogas analyzer (GFM 416 series, UK).

3 Results and Discussion

3.1 *Steady State Performance of IAAB at Different OLRs*

The performance of the anaerobic–aerobic system for POME treatment was monitored to evaluate its performance from the aspect of COD and BOD removal efficiencies at anaerobic and aerobic compartments respectively, as well as methane composition and yield at various loading rates. The stability of the IAAB was evaluated from the aspect of pH, MLSS concentration, and F/M ratio. The optimum operating conditions for IAAB were determined within the range implemented in this study as presented in Table 2. It is expected that the most appropriate OLR and MLSS concentrations will neither be too low or too high, as both conditions will deteriorate the performance of IAAB. Generally, the IAAB achieved high treatment efficiency with overall COD, BOD, and TSS removals of up to 99%, at average OLR of 6.3 ± 4.7 kg COD/m^3 day and total HRT of 10.0 ± 5.9 days. The outcomes of the current study are presented and discussed in the following sections.

The composition of biogas produced by the IAAB is presented in Table 3. The average methane composition of biogas ranges between 60.2–64.4%, compared to those obtained by Malakahmad et al. (2014), where the methane content was found to be 54–75%. Poh and Chong (2014) have also reported that UASB-HCPB reactor have successfully produced biogas with methane content of 42.5–76.1% and the remaining being carbon dioxide when treating POME under thermophilic condition (Poh & Chong, 2014). The high methane content is desirable as it represents the heating value

Table 2 Operating conditions for the anaerobic and aerobic compartment of the IAAB

Operating conditions	Anaerobic	Aerobic
OLR (kg COD/m^3 day)	0–20	0–9.5
HRT (days)	4.59–27.7	4.1–22.7
MLSS (mg/L)	9000–49,600	9000–40,500
DO (mg/L)	–	≥2
pH	6.5–7.4	7.5–8.5

Table 3 The composition of the biogas generated by the IAAB

Component	Average	Range
CH_4 (%)	63.2	60.2–64.4
CO_2 (%)	31.3	30.2–35.1
O_2 (%)	0.35	0.2–4.0
H_2S (ppm)	852	814–1902

of the gas. It is noticeable that <1 vol% of oxygen was picked up by the sensor. The oxygen content may be due to the exposure of the instrument to the atmosphere when the biogas was analyzed. Another possible cause is due to the leakage of oxygen into the anaerobic compartment from the aerobic section of the bioreactor. Nonetheless, the trace of oxygen content is negligible. The hydrogen sulphide generated is expected to be low when methane production is high. This phenomena is explainable by the competition between the sulphate-reducing bacteria with methane-producing bacteria for available hydrogen during anaerobic degradation (Eriksen et al., 2012). However, the traces of hydrogen sulfide in biogas is still unfavorable as it brings about corrosiveness and odor potential of the biogas which may consequent to hazardous situation when being ignited. Hence, it is essential to remove the acidic gas from the biogas before utilization.

From Fig. 3, it can be observed that the IAAB exhibited a stable methane yield which falls in the range of 0.190–0.257 L CH_4/g COD upon operating on the 10th day onwards. The increase in methane yield also corresponded with the increasing MLSS concentration (Sect. 3.3) as operational day increases until the 30th day as shown in Fig. 3.

This shows that the operational condition of the IAAB is conducive for the bacterial activity of the methanogens. The methane yield obtained in the present study is similar to the methane yield of 0.22–0.24 L CH_4/g COD obtained in mesophilic system at lab scale as reported by previous study (Chan et al., 2013). The alignment of the results achieved by the IAAB at pre-commercialized scale with lab scale shows the potential of the proposed technology in providing higher treatment efficiency once further work on optimization is conducted. These results are also used in the development of a simulation model (Chong et al., 2021). In the next section, the effect of OLR and MLSS concentrations would be evaluated to obtain the recommended operating conditions for IAAB.

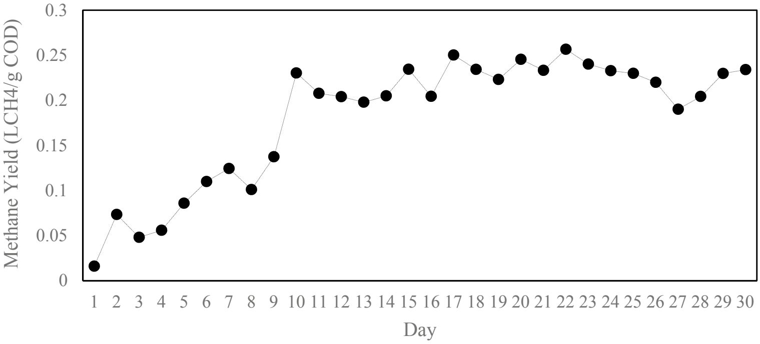


Fig. 3 Methane yield obtained by the IAAB throughout 30 operational days

3.2 *Effect of OLR*

Figure 4 shows the performance of the anaerobic compartment in terms of COD removal efficiencies at various OLRs. OLR was increased from 5 kg COD/m^3 day up to 20 kg COD/m^3 day, testing the maximum loading condition for the design of a potential full scale IAAB system. It can be seen that the anaerobic COD removal efficiency is stable and consistent over 71.70–77.30% as OLR range increases until OLR of 10–12 kg COD/m^3 day. Thereafter, the anaerobic COD removal efficiency experienced a drastic fall to 65.89% at OLR range of 18–20 kg COD/m^3 day. The trend of the results are expected as similar results were portrayed by the previous work conducted, where the anaerobic COD removal was reportedly portraying a drastic decreasing trend in efficiency at approximately OLR of 19.6 COD/L day onwards (Chan et al., 2017). Conversely, the COD removal efficiency in the aerobic compartment was relatively higher and more stable, with an average value of 91 ± 6.1% at OLR ranging from 0.48 to 9.53 kg COD/m^3 day. Similarly, the overall COD removal efficiency of the entire IAAB remained stable, averaged at 95.6 ± 6.6% regardless of the various OLR applied. The effect of OLR on the overall COD removal efficiency was not as straight forward. The overall COD removal efficiency provided by the IAAB system was contributed by the anaerobic and aerobic compartment of the bioreactor respectively. As reported previously, the increment of OLR resulted in lower contribution from anaerobic compartment to the overall COD removal efficiency (Chan et al., 2012, 2017). On the contrary, COD removal efficiency in the aerobic compartment was compensated for the reduction in efficiency posed by the anaerobic zone at high OLR, as the aerobic microorganism activity was promoted. In short, the COD removal efficiencies in the anaerobic and aerobic zones were inversely related.

Rectification on the importance of aerobic system in bioreactor can be proven via present study to ensure treated effluent meets the discharge standard especially when operating at a high loading rate. Nonetheless, an excessively high loading rate will consequent to failure of the final treated effluent in meeting the discharge limit. This

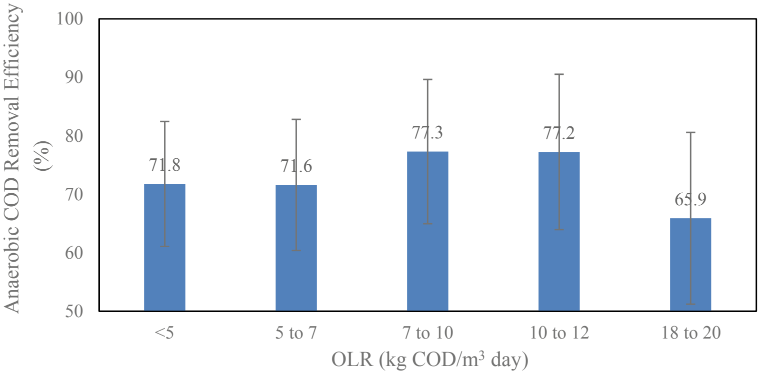


Fig. 4 The anaerobic COD removal efficiency of IAAB at different range of OLR (Chan et al., 2020)

is explainable by the dominant effect of OLR on the performance of the anaerobic zone as this compartment is heavily responsible in removing most of the COD in the wastewater. Additionally, inhibition of the aerobic biomass activity was reported when OLR was increased to 25.0 g COD/L day which consequent to the fall in the COD removal efficiency (Chan et al., 2012). Concurrent to this, some operational issues such as foaming and scum formation were also encountered in anaerobic compartment and this will be discussed in Sect. 3.4.

It is also noticeable that the anaerobic COD removal efficiency is not as high as reported previously. This is expected as the performance of present study have not been optimized to cater to the scaled-up volume of the bioreactor. Furthermore, it is suspected that the recirculation flowrate drawn from the IAAB (<70 m^3/h) by the external centrifugal pump is not sufficiently high enough in providing adequate mixing within the system. Generally, mixing in the anaerobic zone is essential as it promotes the distribution of substrates and microorganisms thoroughly within the digester in achieving homogeneity. On top of that, mixing can overcome the rheological behavior of the nature of slurry which poses complications in attaining turbulence while also forming dead zones inside the digester (Singh et al., 2020). The recommended recirculation flowrate is as suggested in Sect. 3.5. According to Singh et al. (2020), approximately 44% failures of the biogas plants occur due to mixing flaws. Therefore, further work can be done in determining the optimum recirculation flow rate in the anaerobic zone through a multidisciplinary approach which involves the expertise in fluid dynamics and microbiology.

Figure 5 depicts the capability of IAAB in treating POME that exhibits a large range of COD. It can be observed that the anaerobic COD removal efficiency increases as the strength of the wastewater increases. This shows that this technology is effective in treating POME which usually exhibits COD at the range of 85,000–100,000 mg/L (Yap et al., 2020). Undoubtedly, the IAAB technology holds potential for treating a large quantity of high strength wastewater as it is known as a valuable feedstock for anaerobic–aerobic treatment to harness its high COD content for

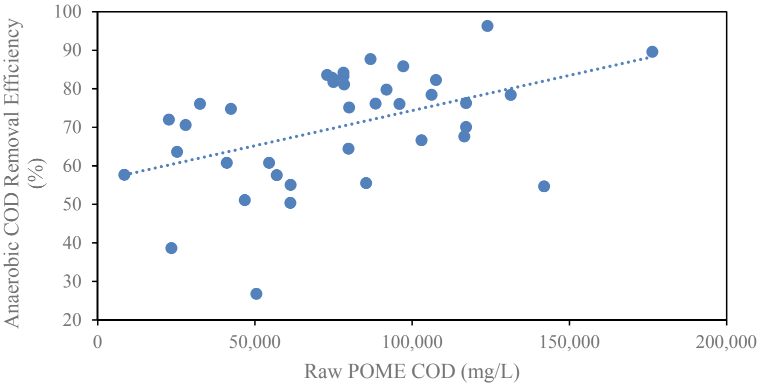


Fig. 5 Anaerobic COD removal efficiency for different COD influent (Chan et al., 2020)

energy generation. Moreover, the present innovation greatly reduces sludge production when it is treated at the anaerobic section of the system (Chan et al., 2009). Subsequently, the aerobic section will counter the fluctuations in the quality of the anaerobically treated effluent. The integration and optimization of both biological treatments are indeed a reliable innovation in overcoming the wastewater produced in this industry.

3.3 Effect of MLSS Concentration and F/M

It is essential to monitor the MLSS concentration and F/M ratio in understanding the ongoing biochemical activity and their variations during the operation, as it greatly signifies the performance of the IAAB. Figure 6 depicts the MLSS concentration in the aerobic and anaerobic compartment of the IAAB throughout the operational days. For the aerobic compartment, it can be observed that the highest MLSS concentration of 38,600 mg/L falls on the 19th day of the operation. The decrease in MLSS concentration is suspected to be brought upon by the increment in OLR. As reported from previous work, MLSS concentration reduces drastically when the anaerobic OLR was increased to 19.5–21.0 kg COD/m^3 day due to wash out of anaerobic sludge with poor settleability (Chan et al., 2017). The initial increase in MLSS concentration shows increasing microbial activity along the days which coincided with the increasing aerobic COD removal. The increase in the population of the microorganism shows that the IAAB is capable in maintaining high biomass concentration to provide efficient treatment on POME. On the other hand, the MLSS concentration in the anaerobic zone is consistent over the range of 15,000–19,000 mg/L which corresponded to the plateau achieved by the methane yield shown in Fig. 3 on 15th days onwards. This means that MLSS concentration at this range is sufficient in providing efficient treatment on the POME while yielding stable methane generation.

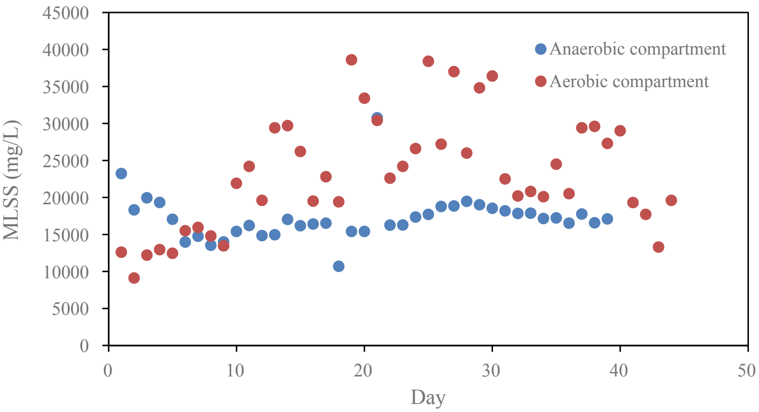


Fig. 6 MLSS concentration along the operational days of the anaerobic and aerobic compartment of IAAB

Figure 7 shows the effect of F/M ratio on the COD removal efficiency. It can be observed that the COD removal efficiency decreases along the increment of F/M ratio in the aerobic compartment. Thus, this occurrence has consequent to the reduction in the overall COD removal as the anaerobic effluent is no longer being further biodegraded at an optimum condition. Since F/M ratio is dependent on the OLR and MLSS concentration, the result is expected as the system experienced a shock loading where the sudden increase in the organic matter was unable to be treated effectively by the microorganisms. Similar results were also reported from previous work where a higher bacterial population is required to treat OLR higher than 11.7 kg COD/ m^3 day (Chan et al., 2013).

The decrease in the overall COD removal efficiency coincides with the final BOD effluent of the system as presented in Fig. 8. It can be observed that majority of the

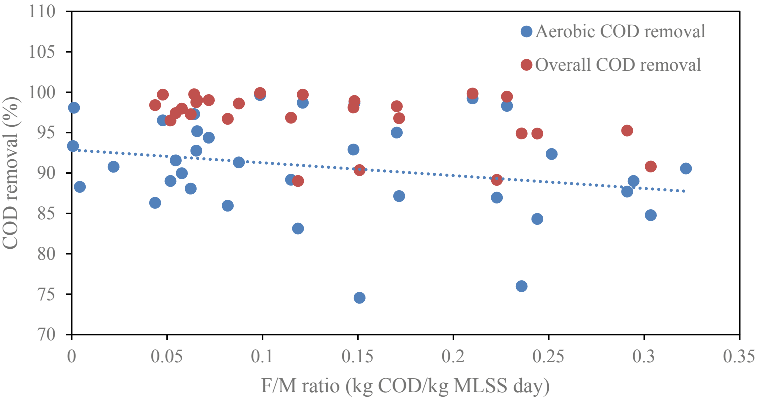


Fig. 7 The effect of F/M ratio on the aerobic and overall COD removal efficiency

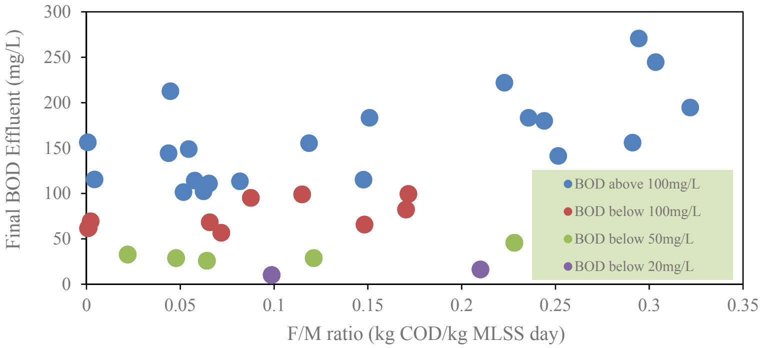


Fig. 8 The effect of F/M ratio on the final BOD effluent

sample exhibited BOD above 100 mg/L which indicates poor BOD removal when F/M ratio increases (Fig. 8). The present study outcome was also reflected by the results published by Lateef et al. (2013), where F/M ratio of 0.21–0.98 kg BOD/kg MLVSS day was accounted for the BOD removal efficiency of 98.3–84.5% (Lateef et al., 2013). Diez et al. (2002) has also reported a decrease in BOD removal at high F/M ratio above 0.2 g BOD/MLVSS day. It is also worth noticing that some samples exhibited BOD above 100 mg/L when F/M ratio is too low (<0.05 kg COD/kg MLSS day). This is explainable by the shortage of food for adequate bacterial growth in the system hence, poor biodegradation of the organic matter occurred. Nonetheless, the inverse relationship between F/M ratio and the organic removal efficiency proves that increasing F/M ratio does not favor the performance of the IAAB which further rectifies the effect of the OLR increment on treatment efficiency as discussed in the previous section.

3.4 Operational Issues Faced by IAAB

During the start-up and steady state operation of 200 days, there are few operational problems faced by anaerobic and aerobic compartment. For instance, foaming issues faced by both anaerobic and aerobic compartment, whereas scum formation occurred in anaerobic compartment. This is possibly due to the inconsistent or changes in influent conditions which created a shock loading state to the plant. In addition, the sudden change in POME influent can result in lower effluent quality as insufficient contact time is observed between the microbial community and the POME substrate. The detailed operational problems, their root causes and rectifications methods will be discussed in the following sub-sections.

3.4.1 Anaerobic Compartment

The anaerobic process and top-notch performance are affected by the presence of microorganism to the available substrates and nutrients, appropriate pH, temperature, HRT, Solid Retention Time (SRT), and the distribution of POME substrate (Kress et al., 2018). The former which all influenced by the mixing behavior. According to Kariyama et al. (2018) and Singh et al. (2019), various issues such as failure in methane yield, flawed stabilization of raw slurry, reduction in digester volume, high operational cost, non-homogenous distribution of temperature and substrate, short circuiting, occurrence of sediment at bottom of digester, dead zone, and especially scum formation are mainly due to inadequate mixing.

The phenomena of scum formation is of common problems affecting the full-scale anaerobic digester (Kariyama et al., 2018). In this study, scum formation was observed on days 56–59 (Fig. 9a) due to the high OLR (18 kg COD/m^3 day) applied and therefore, high COD effluent (38,000–73,800 mg/L) and low COD removal (25–55%) were observed. Some studies have shown that substrate with high concentration of fatty acids or high grease content in the influent are among the cause for the formation of scum which will diminish the efficiency of anaerobic digester (Halalsheh et al., 2005; Pagilla et al., 1997). This is true as the current treatment for POME contains high amount of oil and grease, ranging from 130 to 18,000 mg/L.

As suggested by Kshirsagar and Pawar (2018), the deformation of scum can be solved by increasing the surface velocity and designing concrete flaps at the baseline of the anaerobic digester. Furthermore, the geometry and configurations of anaerobic digester plays a vital role where an egg-shaped digester is much preferable as compared to cylindrical digester in terms of maintaining homogeneity, uniform mixing and reducing dead zones (Singh et al., 2020). A similar approach by Kobayashi et al. (2013) observed that there is no scum formation when the OLR is keeping low (5–10 kg COD/m^3 day) and stressed that potential of scum formation is mostly related to the increase in OLR and HRT shortening. Besides, too low HRT would result in an incomplete degradation of POME substrate (especially oil

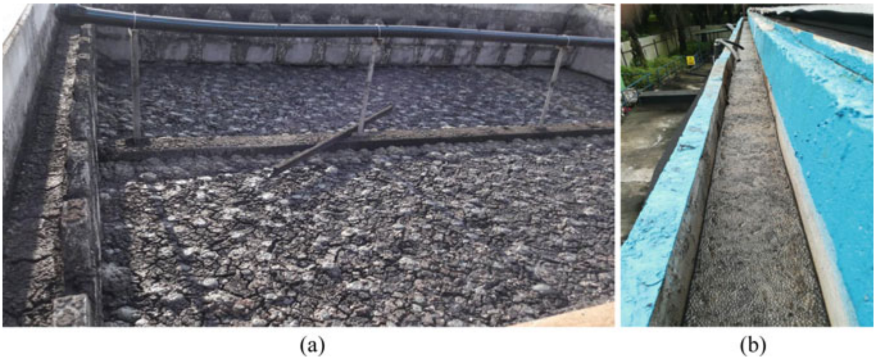

(a) (b)

Fig. 9 **a** Scum formation, **b** foaming and grease) or bacteria wash-out at an early stage. Therefore, to rectify this scum problem effectively, the OLR was immediately reduced to 5 kg COD/m^3 day. At the same time, the recirculation rate was increased to 140 m^3/h to breakdown the scum layer while providing better mixing to the digester as discussed earlier. Thereafter, the anaerobically treated effluent COD was gradually reduced to 13,800 mg/L on day 60.

Besides scum formation, foaming is also a serious operational problem usually occurs in full-scale biogas plants at wastewater treatment plants (WWTPs) (Nguyen et al., 2019). Foaming causes inefficient gas recovery, blockages of gas mixing, fouling of gas collection pipes and covering the digester wall with foam solid (Ganidi et al., 2009; Pagilla et al., 1997). Besides, it will limit the methane production and incur high manufacturing cost when taking into account of cleaning, repairing and maintenance (Ganidi et al., 2009; Moeller & Görsch, 2015; Westlund et al., 1998). Although numerous studies have addressed for this reoccurring phenomenon, the exact principle and concept of foaming in anaerobic digestion is still not fully understood (Barjenbruch et al., 2000).

In this study, foaming problem was also reported on day 66 (Fig. 9b) and low methane production was observed (0.11 L CH_4/g COD). When foam was beginning to build up significantly, the recirculation rate was immediately reduced to 70 m^3/h. This is because high recirculation rate of 140 m^3/h (which was implemented on day 56) has led to over mixing condition. This has significantly reduced the wastewater surface tension, and thus leading to this foaming problem. Apart from this, intermittent mixing of 140 m^3/h for every time interval of 30 min was also incorporated in the anaerobic compartment. Both approaches were deemed feasible, as foaming condition is reduced gradually and the performance of the anaerobic compartment was back to normal after 10–15 days of implementation of these approaches. Therefore, it can be concluded that adequate mixing (recirculation rate) is of utmost importance to maintain optimal anaerobic digester function while minimizing the operational problems.

3.4.2 Aerobic Compartment

In aerobic compartment, microorganism activity and adequate control of MLSS plays a significant role in the activated sludge process as unfavorable conditions would affect the effluent quality (de los Reyes, 2010). The most common problems during the aerobic treatment includes foaming, sludge bulking, and sludge rising (Khodabakhshi et al., 2015). As dictated by Fryer et al. (2011), large volume of foam can lead to undesirable operational conditions such as blockage in pipes, exposure of pathogens, reduced plant performance, reduction in oxygen transfer, walkway and plant monitoring equipment obstruction. The aforementioned issues are faced by 40% of overall wastewater treatment plants, 78% of existing activated sludge systems in the country and most major problem encountered in South Africa (Khodabakhshi et al., 2015). Generally, foaming and bulking problems are associated to various of filamentous bacteria, production of extracellular polymers, sludge treatment facilities which contains oil and grease, and synthesis of bio-surfactant in the presence of hydrophobic substrate (Pal et al., 2014). In addition, the three main components for stable foam formation required presence of air bubbles, surfactants, and hydrophobic cells (Petrovski et al., 2011).

There are many types of foaming formation either chemically or biologically, and both must undergo dispersion of gas in a liquid. First, chemical foams are derived mainly from excess surfactant (white foams), which applies to most pharmaceutical, cosmetics, textiles, food, paper and biotechnology industries (Collivignarelli et al., 2020). Nonetheless, this study follows the biological approach (brown foams) which is related to the growth of filamentous bacteria named "foam former" or bacterial-synthesized hydrophobic high-molecular weight substances in MLSS (Fig. 10a) which was detected on day 68 (30 March 2018). The foam appearance and characteristics in the current study are observed to be brownish-like which is associated to high F/M ratio of 0.22–0.32 kg COD/kg MLSS, high OLR of 4.23–9.53 kg COD/m^3 day, and high grease and oil content of 10,000–18,000 mg/L. This is due to the foaming problem occurred in anaerobic compartment (day 66) where excessive sludge/foam from the anaerobic compartment was carried over to the aerobic compartment. Overall, insufficient MLSS results in lesser microorganism population for the degradation process in aerobic compartment which also contributes to higher F/M ratio. Thus, inefficient degradation mechanism leads to higher oil and grease concentration which end up with increasing foaming issues.

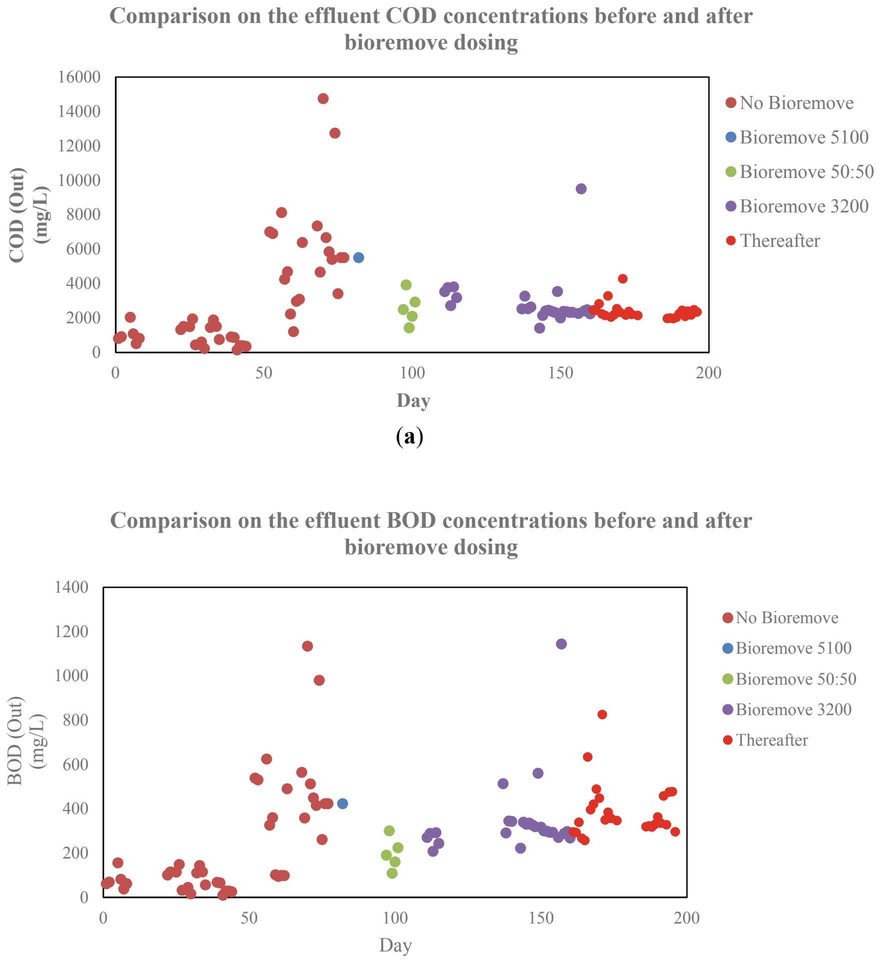
Various ways for the treatment of foaming issues can be distinguished into short-term and long-term control methods. Short-term control involves chlorination, polymer and coagulation addition, while long-term control involves alteration in aeration, biomass concentration, influent waste septicity (H_2S and organic acids), and nutrient addition (Richard, 2003). According to Pal et al. (2014), short-term methods are of most favorable for rapid and effective regulation of activated sludge


(a) (b)

Fig. 10 Day 1: 30 March 2018 (**a**) 5 April 2018 (**b**) Foam condition after 5 days with Bioremove 5100 foaming, however the usage of chemical solutions could be expensive for long-term usage (Tsang et al., 2008) and potential of forming undesirable by-products such as trihalomethanes (THMs) (Caravelli et al., 2003). The former can be solved by alternating toward biological approach, Bioremove from Novozymes that can improve digester performance, resulting in cost-efficient and more sustainable to enhanced COD removal and stable plant operation (reduces foaming issues) (Novozymes, 2021b). Bioremove is defined as blend of microorganisms in powder state for the biological degradation of substrate, which can be utilized in most wastewater treatment plants (Chempoint, 2021). The solution of Bioremove is suitable to treat highly complex waste streams, choosing from a large spectrum of microorganisms that could cater a wide range of organic substrate to ensure the compliance of the plant. The simple approach of Bioremove greatly improved the plant stability, and approximately 16% COD reduction in effluent concentrations without the need to invest in capital investment (e.g. reactor volume) (Novozymes, 2021a). On the other hand, many operators have tried to resolve forming issues by reducing the aeration for long-term focus, yet results in higher filament growth rate (Richard, 2003). Therefore, in this experimental study, rectification has been decided upon aerobic compartment, in which Bioremove by Novozymes will be utilized. The application of Bioremove 5100 dosing has proven to reduce the foaming conditions after 5 days as seen in Fig. 10a, b.

While application of Bioremove seems to counteract the foaming problems, other parameters such as COD and BOD removal efficiencies will be affected as shown in Fig. 11. Therefore, comparison between Bioremove 3200, Bioremove 5100 and combination of both at 50:50 ratio will determine the best overall results for COD and BOD removals along with foaming reduction (Fig. 11). Bioremove 5100 is able to control the foaming but unable to effectively reduce COD and BOD. Besides, effluent produced by using Bioremove 5100 alone has a darker color with a thin layer of oil. On the other hand, Bioremove 3200 is able to reduce COD and BOD but produce excessive foam. Effluent produced by using Bioremove 3200 alone has a light brown color, however no oil layer is observed. Finally, combination of Bioremove 5100 and Bioremove 3200 at ratio of 50:50 is the optimum choice where lower effluent COD and BOD ranging from 1420 to 3910 mg/L and 109–310 mg/L, respectively were observed.

In conclusion, anaerobic compartment plays a vital role in the overall performance of IAAB as it removes most of the organic fraction from POME, and most importantly, any operational problems occurred in the anaerobic compartment will impact the performance of the subsequent aerobic compartment. This is because the scum or foam formed in the anaerobic compartment will eventually pass through the aerobic compartment, which will result in overall performance deterioration (approximately 40–70%). Therefore, it is important to maintain the IAAB at the recommended operating conditions so that the aforementioned operational problems could be minimized while achieving high treatment efficiency. The recommended operating conditions will be discussed in the next section.


Comparison on the effluent COD concentrations before and after bioremove dosing

(a)

Comparison on the effluent BOD concentrations before and after bioremove dosing

(b)

Fig. 11 Effluent quality with/without Bioremove dosing: **a** COD concentrations **b** BOD concentrations

3.5 Recommended Operating Conditions for IAAB

The operating conditions suggested for the anaerobic and aerobic compartments in IAAB are as presented in Tables 4 and 5 respectively. As discussed from the previous section, increment in OLR will result to lower anaerobic performance but better aerobic performance. Despite that, excessively high OLR will result to failure in the overall system in treating the effluent in meeting the stringent discharge standards as well as inhibiting methanogenesis which ultimately leads to lower methane production. This is explainable by the dominant effect of OLR on the performance of the anaerobic zone. In addition, the anaerobic compartment is heavily responsible in removing most of the organic matter found in the wastewater. Referring to the present work's outcome, OLR of 7–12 kg COD/m^3 day is the most appropriate range in attaining stable and consistent overall COD removal efficiency. The lower range of OLR is not selected as higher loading capacity is necessary in reducing the bioreactor volume as well as the capital costs. It was observed that consistent methane yield was attained over the MLSS range of 18,000–19,000 mg/L (Fig. 6). In previous work, low MLSS concentration was reported to be incapable in sustaining high bioactivity in the bioreactor. On the other hand, excessively high MLSS concentration will consequent to low COD removal, long sludge settling time and high concentration of suspended solid in the effluent (Chan et al., 2013). Hence, the MLSS concentration is proposed to be fixed at 19,000 mg/L. Mixing features are also incorporated to the anaerobic zone to promote intimate contact between the microorganisms with the substrate within the system. This can be done by providing either intermittent of 140 m^3/h for every time interval of 30 min or continuous recirculation rate of 70 m^3/h respectively (Sect. 3.5). The COD removal efficiency set for the anaerobic zone will be around 70–85% to ensure that the anaerobic effluent has adequate nutrients available for the aerobes to carry out its biodegradation under the presence of oxygen. Hence, the COD removal is set to be sufficient but not excessively high to ensure effective aerobic function in the next subsequent stage. The methane yield is expected to be 0.22 L CH_4/g COD with biogas production of 63% methane content. Based on this, the IAAB is expected to be generating power of 390 kW by utilizing the methane production of 6 m^3/h (Table 4).

The F/M ratio in the aerobic compartment is suggested to operate at below 0.17 kg COD/kg MLSS day as the treatment efficiency decreases above the value mentioned. The present work's outcome has also proven that the IAAB is able to achieve a final BOD effluent below 100 mg/L with 45% of compliance. As mentioned in Sect. 3.3, higher COD removal efficiency was attained when operating at lower F/M ratio. Moving on, the MLSS concentration is recommended to be within the range of 19,000–26,000 mg/L in ensuring that very high aeration is not required in the aerobic compartment as such implementation will increase the operating cost. DO

Table 4 Recommended operating conditions for anaerobic compartment

Anaerobic	Recommended range
OLR (kg COD/m^3 day)	7–12
MLSS concentration (mg/L)	19,000
Recirculation rate	140 m^3/h intermittent mixing for 30 min every hour 70 m^3/h continuous mixing
COD removal (%)	70–85
Methane yield (LCH_4/g COD)	0.22
Methane purity (%)	63%
Power generation	6 m^3/h, COD 80,000 mg/L, 390 kW @40% gas engine efficiency

Table 5 Recommended operating conditions for aerobic compartment

Aerobic	Recommended range
F/M (kg COD/kg MLSS day)	≤0.17
MLSS (mg/L)	19,000–26,000
DO (mg/L)	≥2
COD removal (%)	85–99.6
Energy consumption (kW/day)	35

is supplied at 2 mg/L and above to sustain the bacterial population of aerobes to provide decent biodegradation of the wastewater (>80% BOD removals). With the suggestions above, final COD removal of 85.0–99.6% has been achieved by this pre-commercialized IAAB. The energy consumption of the aerobic zone is estimated to be 35 kW per day. The operating conditions presented in Table 5 are proposed for the operation of IAAB in attaining high treatment efficiency (overall COD removal efficiency >99%) as well as high methane generation (>0.22 L CH_4/g COD).

4 Conclusion

The Integrated Anaerobic–Aerobic Bioreactor (IAAB) has been successfully scaled up into pre-commercialized scale while achieving high overall COD, BOD, and TSS removals of more than 99% along with high methane yield (>0.22 L CH_4/g COD) containing 63% of methane purity. Undoubtedly, the present study has proven that various factors including OLR and MLSS concentration posed significant effects on the performance of the IAAB. With consideration of the effects brought upon by different factors discussed in this chapter, the anaerobic zone of the IAAB is suggested to operate at OLR of 7–12 kg COD/m^3 day under MLSS concentration of 19,000 mg/L, and with intermittent and continuous mixing through recirculation flowrate of 140 m^3/h at interval of 30 min and 30 m^3/h respectively. The aerobic zone is proposed to operate below F/M ratio of 0.17 kg COD/kg MLSS day under MLSS concentration of 19,000–26,000 mg/L with DO supply of more than 2 mg/L. In commercial setting, anaerobic compartment is prone to problems such as scum formation and foaming issue due to insufficient mixing and over mixing, respectively and these can be solved by adjusting the recirculation rate. Besides, the occurrence of foaming in aerobic compartment has been successfully reduced by dosing Bioremove 5100 and Bioremove 3200 at ratio of 50:50. Results show that it is important to maintain the anaerobic compartment at the recommended operating conditions so that the aforementioned operational problems could be minimized. Any operational problems occurred in the anaerobic compartment will significantly impact the performance of the subsequent aerobic compartment. Therefore, future improvement and recommendations in terms of performance of IAAB would be focused on process optimization of the anaerobic compartment, particularly in the aspect of microbiology, fluid dynamics, and mass transfer in slurry viscous conditions. Satisfactory results from this study will enable a closer step toward the industrial revolution for the treatment of POME. The successful achievement of IAAB toward commercialization will assist palm oil industry in tackling climate change and maintaining water quality brought upon by the conventional settings which greatly depletes the ozone layer of the earth. Certainly, the innovation and high performance of IAAB will be brought upon safe water and sanitation for human beings and accessibility to green and sustainable energy.

Acknowledgements The authors gratefully acknowledge the financial support from The University of Nottingham Malaysia and Havys Oil Mill.

References

Akhbari, A., Kutty, P. K., Chuen, O. C., & Ibrahim, S. (2020). A study of palm oil mill processing and environmental assessment of palm oil mill effluent treatment. *Environmental Engineering Research, 25*(2), 212–221.

Association, A. P. H., Association, A. W. W., Federation, W. P. C., & Federation, W. E. (1912). *Standard methods for the examination of water and wastewater*. American Public Health Association.

Barjenbruch, M., Hoffmann, H., Kopplow, O., & Tränckner, J. (2000). Minimizing of foaming in digesters by pre-treatment of the surplus-sludge. *Water Science and Technology, 42*(9), 235–241.

Caravelli, A., Contreras, E. M., Giannuzzi, L., & Zaritzky, N. (2003). Modeling of chlorine effect on floc forming and filamentous micro-organisms of activated sludges. *Water Research, 37*(9), 2097–2105.

Cervantes, F., Pavlostathis, S., & van Haandel, A. (2006). *Advanced biological treatment processes for industrial wastewaters—Principles & applications*, IWA Publishing.

Chan, Y. J., Chong, M. F., & Law, C. (2013). Optimization of palm oil mill effluent treatment in an integrated anaerobic-aerobic bioreactor. *Sustainable Environment Research, 23*, 153–170.

Chan, Y. J., Chong, M. F., & Law, C. L. (2012). Start-up, steady state performance and kinetic evaluation of a thermophilic integrated anaerobic–aerobic bioreactor (IAAB). *Bioresource Technology, 125*, 145–157.

Chan, Y. J., Chong, M. F., & Law, C. L. (2017). Performance and kinetic evaluation of an integrated anaerobic-aerobic bioreactor in the treatment of palm oil mill effluent. *Environmental Technology, 38*(8), 1005–1021.

Chan, Y. J., Chong, M. F., Law, C. L., & Hassell, D. G. (2009). A review on anaerobic–aerobic treatment of industrial and municipal wastewater. *Chemical Engineering Journal, 155*(1–2), 1–18.

Chan, Y. J., Hue, F. S., Chong, M. F., Ng, D. K. S., & Lim, L. K. (2020). Pre-commercialized integrated anaerobic-aerobic bioreactor (IAAB) for palm oil mill effluent (POME) treatment & biogas generation. *Journal of Oil Palm, Environment & Health, 11*, 57–66.

Chong, J. W. R., Chan, Y. J., Chong, S., Ho, Y. C., Mohamad, M., Tan, W. N., Cheng, C. K., & Lim, J. W. (2021). Simulation and optimisation of integrated anaerobic-aerobic bioreactor (IAAB) for the treatment of palm oil mill effluent. *Processes, 9*, 1124.

Chempoint. (2021). Novozymes bioaugmentation.

Collivignarelli, M. C., Baldi, M., Abbà, A., Caccamo, F. M., Carnevale Miino, M., Rada, E. C., & Torretta, V. (2020). Foams in wastewater treatment plants: from causes to control methods. *Applied Sciences, 10*(8).

de los Reyes, F. L. (2010). In K. N. Timmis (Ed.), *Handbook of Hydrocarbon and lipid microbiology* (pp. 2401–2411), Springer.

Diez, M. C., Castillo, G., Aguilar, L., Vidal, G., & Mora, M. L. (2002). Operational factors and nutrient effects on activated sludge treatment of Pinus radiata kraft mill wastewater. *Bioresource Technology, 83*(2), 131–138.

Eriksen, J., Andersen, A. J., Poulsen, H. V., Adamsen, A. P., & Petersen, S. O. (2012). Sulfur turnover and emissions during storage of cattle slurry: Effects of acidification and sulfur addition. *Journal of Environmental Quality, 41*(5), 1633–1641.

Frostell, B. (1983). Anaerobic-aerobic biological treatment of starch industry waste waters. *Starch - Stärke, 35*(6), 185–189.

Fryer, M., O'Flaherty, E., & Gray, N. F. (2011). Evaluating the measurement of activated sludge foam potential. *Water, 3*(1), 424–444.

Ganidi, N., Tyrrel, S., & Cartmell, E. (2009). Anaerobic digestion foaming causes—A review. *Bioresource Technology, 100*(23), 5546–5554.

Halalsheh, M., Koppes, J., den Elzen, J., Zeeman, G., Fayyad, M., & Lettinga, G. (2005). Effect of SRT and temperature on biological conversions and the related scum-forming potential. *Water Research, 39*(12), 2475–2482.

Kariyama, I. D., Zhai, X., & Wu, B. (2018). Influence of mixing on anaerobic digestion efficiency in stirred tank digesters: A review. *Water Research, 143*, 503–517.

Khodabakhshi, N., Asadollahfardi, G., & Shahriarinia, E. (2015). Removal of foaming from industrial wastewater treatment plants. *Water Practice and Technology, 10*(3), 415–423.

Kobayashi, T., Wu, Y.-P., Xu, K.-Q., & Li, Y.-Y. (2013). Effect of mixing driven by siphon flow: Parallel experiments using the anaerobic reactors with different mixing modes. *Energ., 6*(8), 4207–4222.

Kress, P., Nägele, H.-J., Oechsner, H., & Ruile, S. (2018). Effect of agitation time on nutrient distribution in full-scale CSTR biogas digesters. *Bioresource Technology, 247*, 1–6.

Kshirsagar, V. S., Pawar, P. M. (2018). Mixing performance improvement by passive modifications in an anaerobic digester design. *Materials Today: Proceedings, 5*(9, Part 3), 20600–20607.

Lateef, A., Nawaz Chaudhry, M., & Ilyas, S. (2013). Biological treatment of dairy wastewater using activated sludge. *ScienceAsia, 39*, 179.

Malakahmad, A., Lahin, F. A., & Yee, W. (2014). Biodegradation of high-strength palm oil mill effluent (POME) through anaerobes partitioning in an integrated baffled reactor inoculated with anaerobic pond sludge. *Water, Air, & Soil Pollution, 225*(3), 1883.

Moeller, L., & Görsch, K. (2015). Foam formation in full-scale biogas plants processing biogenic waste. *Energy, Sustainability and Society, 5*(1), 1.

MPOC. (2020). Malaysian Palm Oil Industry.

Nguyen, L. N., Johir, M. A. H., Commault, A., Bustamante, H., Aurisch, R., Lowrie, R., & Nghiem, L. D. (2019). Impacts of mixing on foaming, methane production, stratification and microbial community in full-scale anaerobic co-digestion process. *Bioresource Technology, 281*, 226–233.

Novozymes. (2021a). BioRemove 1100 case study.

Novozymes. (2021b). Water & Waste.

Pagilla, K. R., Craney, K. C., & Kido, W. H. (1997). Causes and effects of foaming in anaerobic sludge digesters. *Water Science and Technology, 36*(6), 463–470.

Pal, P., Khairnar, K., & Paunikar, W. N. (2014). Causes and remedies for filamentous foaming in activated sludge treatment plant. *Global Nest Journal, 16*, 762–772.

Petrovski, S., Dyson, Z. A., Quill, E. S., McIlroy, S. J., Tillett, D., & Seviour, R. J. (2011). An examination of the mechanisms for stable foam formation in activated sludge systems. *Water Research, 45*(5), 2146–2154.

Poh, P. E., & Chong, M. F. (2014). Upflow anaerobic sludge blanket-hollow centered packed bed (UASB-HCPB) reactor for thermophilic palm oil mill effluent (POME) treatment. *Biomass and Bioenergy, 67*, 231–242.

Richard, M. (2003). Activated sludge microbiology problems and their control.

Singh, B., Szamosi, Z., & Simenfalvi, Z. (2020). Impact of mixing intensity and duration on biogas production in an anaerobic digester: A review. *Critical Reviews in Biotechnology, 40*(4), 508–521.

Singh, B., Szamosi, Z., & Siménfalvi, Z. (2019). State of the art on mixing in an anaerobic digester: A review. *Renewable Energy, 141*, 922–936.

Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2004). Wastewater engineering—Treatment and reuse (4th ed.). Metcalf & Eddy.

Tsang, Y. F., Sin, S. N., & Chua, H. (2008). Nocardia foaming control in activated sludge process treating domestic wastewater. *Bioresource Technology, 99*(9), 3381–3388.

Westlund, Å. D., Hagland, E., & Rothman, M. (1998). Foaming in anaerobic digesters caused by Microthrix parvicella. *Water Science and Technology, 37*(4), 51–55.

Yacob, S., Hassan, M. A., Shirai, Y., Wakisaka, M., & Subash, S. (2005). Baseline study of methane emission from open digesting tanks of palm oil mill effluent treatment. *Chemosphere, 59*(11), 1575–1581.

Yap, C. C., Chan, Y. J., Loh, S. K., Supramaniam, C. V., Soh, A. C., Chong, M. F., Chew, C. L., & Lim, L. K. (2020). Comparison of different industrial scale palm oil mill effluent anaerobic systems in degradation of organic contaminants and kinetic performance. *Journal of Cleaner Production, 262*, 121361.