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Performance Evaluation of Tubular Ceramic Membrane for Palm Oil Mill Effluent Treatment

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ABSTRACT

Palm oil industry is one of the most important agriculture sectors in Malaysia. However, this industry produces a huge amount of palm oil mill effluent (POME) which contains impurities that will pollute the environment. Hence, POME has to be treated before it can be safely discharged to the environment. This study aims to evaluate the effectiveness of tubular ceramic membranes with different pore sizes (0.2 µm, 450 Da, and 200 Da) for the removal of turbidity and chemical oxygen demand (COD) in POME. It was found that all of the ceramic membranes were capable to achieve more than 99% of turbidity removal through size exclusion mechanism since the particles were larger in size as compared to membrane pores. On the other hand, the reduction of COD was ineffective since the dissolved organic substances in POME could penetrate the membrane and thus resulted in low removal efficiency. Flux decline was recognisable only when treated with the 0.2 µm membrane. It was attributed to its higher initial flux (16 $Lm^{-2}h^{-1}$) that imposed larger permeation drag and brought more impurities to quickly cover the membrane surface and clog the membrane pores during the initial filtration process. Chemical cleaning was able to recover 77-83% of the flux and this shows that some of the impurities were still persisting in the membrane. The tested membranes were capable to fully remove the suspended solids and could serve as a good pre-treatment process for subsequent COD reduction treatment process.

Keywords: Membrane cleaning; membrane fouling; palm oil mill effluent; tubular ceramic membrane; wastewater treatment

INTRODUCTION

Oil palm is one of the most important agricultural commodities, contributing 3.8% of Malaysia's Gross Domestic Product and providing millions of job opportunities (associated upstream and downstream industries) in Malaysia (Department of Statistics Malaysia 2018). With the growing world demand of palm oil in various applications (food industries as in cooking oil, ice cream, salad dressing and supplements/vitamins; oleo-chemical such as surfactants, cosmetics, lubricant, soap and printing ink), the extraction and production of crude palm oil has been accelerated to meet the market demand (Malaysian Palm Oil Board 2019). Associated with the increased extraction of palm oil is the production of palm oil mill effluent (POME), which is a high strength agricultural wastewater that presents a technical and environmental challenge to the mill operators (Iskandar et al., 2018). POME is a thick brownish colloidal effluent that is made up of 95% water and 4-5% suspended solids. POME contains high Chemical Oxygen Demand (COD, averaged at 50000 ppm), Biochemical Oxygen Demand (BOD, averaged at 25000 ppm), and various nutrients (nitrogen, phosphorus, and potassium) in the concentration range of several hundreds to thousands part per million. Discharge of inappropriately treated POME to the environment will lead to serious pollution issues, such as contamination of water resources and disruption to aquatic ecosystems due to eutrophication (Wu et al. 2010).

To ensure compliance with the discharge regulation, palm oil operators in Malaysia have started to transform the POME management strategy from merely treating it to resource recovery approach. The conventional treatment process - open lagoon (ponding system), has long been criticized due to its time and space-consuming need as well as the emission source of greenhouse gases (biodegradation of organic substance in POME by microbes) (Arun et al. 2017). This practice has since been advocated to be replaced with more environmentally friendly treatment technologies, such as anaerobic digestion where the biological degradation of organic substances (translated to reduction of COD) in

POME is conducted in a closed environment to capture the biogas (methane). It was reported that the harvested biogas can be used to supply electricity for internal consumption in the mill, helping the palm oil industry to cut down the reliance on non-renewable coal-based electricity and moving towards sustainable development while reducing the pollution issues of POME (Choong et al. 2018).

The adoption of anaerobic digestion advanced technology has helped to drastically remove 90% of the COD in POME and at the same time mitigate the emission of greenhouse gases (Tabassum et al. 2015). However, the anaerobically treated POME is still laden with impurities that can pollute the environment and are incompliant with the discharge regulation. In the past decades, numerous technologies such as coagulation, adsorption, advanced oxidation process, membrane filtration, biological treatment have been evaluated for their feasibility in treating POME (Liew et al. 2014). Though these technologies can help to reduce the impurities (suspended solids, nutrients, oil and grease, and COD) present in POME to a certain extent, they are not widely adopted as standard treatment process for POME. These could be due to costing issues, where intensive chemical and material consumption, along with high capital and operational costs, are required to ensure efficient removal of impurities for safe discharge.

Statistical data has shown that palm oil industry consumes an abundance of water (1.5 m^3 of water for each 1 ton of fresh fruit bunch operation) and half of this is discharged as POME (Hosseini and Wahid, 2015). The recovery and reuse of water from POME has since been an attractive interest pursued by researchers to realize the goal of water reclamation and reuse from POME. Membrane technology has been known as a highly-effective filtration process that has a proven track record in treating wastewater and producing water of high quality for industrial reuse (Kamali et al. 2019; Ghani et al. 2018; Subramaniam et al. 2017; Tabassum et al. 2015). However, majority of these studies have been conducted using polymeric-based membrane where it is susceptible to fouling phenomena and limited cleaning options. Since POME contains a high load of suspended solids that will block the permeation of water through the membrane, fouling is an inevitable issue encountered by membrane which requires cleaning to restore the performance.

Fouling is the degradation of membrane performance (in terms of treated water permeation and quality) due to the presence of impurities (foulant) on the membrane surface, mostly through deposition and formation of foulant cake layer that blocks the passage of water through the membrane (Ang et al. 2017). Fouling propensity is obviously high for POME treatment using membrane technology due to the presence of abundant suspended impurities in POME. To recover the integrity of membrane process, the foulant has to be removed through cleaning approach. Membrane cleaning is a process that utilizes medium (clean water, oxidant, acid, or alkali) to remove the foulant from clogging the membrane surface (Zsirai et al. 2018). For instance, it has been shown that chemical cleaning such as alkali managed to redeem the membrane flux back to its initial level, indicating the high efficiency of the cleaning process (Li et al. 2018; Ang et al. 2015). However, the popularly used polymeric membrane is highly vulnerable to chemical attack, rendering the practicality of membrane cleaning to restore the performance. In view of this, ceramic membrane which is fabricated from ceramic material has received more attention recently due to its chemical resistance characteristics. This indicates that the fouled ceramic membrane can undergo robust and thorough cleaning for the restoration of performance (Kimura and Uchida, 2019). Thus far, the evaluation of ceramic membrane for POME treatment has not been widely reported. Ceramic membrane which is resistant to chemical and physical cleaning possesses the potential to treat a high strength wastewater such as POME.

Hence, this study aims to investigate the potential of ceramic membrane for POME treatment and at the same time evaluate the reusability of the ceramic membrane after cleaning process. Tubular ceramic membrane of different sizes (0.2 µm, 450 Da, and 200 Da) and different treatment sequences will be used in the study. The cleaning approaches include using ultra-pure water, hydrochloric acid (HCl), sodium hydroxide (NaOH), and potassium hydroxide (KOH). Performance in terms of membrane flux and impurities rejection at different membrane treatment sequences were used for evaluation. Since POME is laden with high load of suspended solids (represented by turbidity) and COD, the focus of this study was on the removal efficiencies of these impurities.

METHODOLOGY

MATERIALS

All the chemicals used in this study were of analytical grade. Chemicals used for membrane cleaning process were HCl (J.T. Baker, Thailand), KOH (J.T. Baker, Sweden), and NaOH (R&M Chemical, Malaysia). Ultra-pure water with a quality of 18 $M\Omega.cm^{-1}$ was used to prepare all chemical solutions and membrane cleaning. Raw POME sample was obtained from the East Mill Sime Darby Palm Oil Plantation located at Carey Island, Selangor, Malaysia. The collected sample was preserved in the cold room, at temperature maintained below 4 °C. Existing tubular ceramic membranes (Fraunhofer Institute for Ceramic Technologies and Systems, Hermsdorf, Germany) were used for this filtration study. Two of the membranes have a nominal molecular weight cut-off of 450 and 200 Da, which fell in the range of nanofiltration. The other membrane belongs to microfiltration with a pore size of 0.2 µm. Each membrane has an effective area of 55 cm^2 and an effective length, outer and inner diameter of 250, 10, and 7 mm, respectively (Fujioka et al. 2018). The tubular membranes were made from aluminum oxide (α-Al_2O_3). Additionally, the top surfaces of 450 Da and 200

Da membranes were covered by a layer of TiO_2 to grant it a tight separation property of nanofiltration.

EXPERIMENT SETUP

For the filtration experiment, the POME was diluted by mixing 100 ml of POME with 400 ml of ultra-pure water. The purpose of dilution was to mimic the quality of anaerobically treated POME (based on the COD level of treated POME). The tubular membranes were operated in inside-out mode and were installed in a stainless steel housing. As shown in Figure 1, the experimental setup comprised tubular membranes, feed and product reservoirs, pressure gauge, and syringe pump (New Era Pump Systems, USA).

EXPERIMENT PROTOCOLS (FILTRATION AND CLEANING)

Before the start of experimental run with POME, the tubular membrane was flushed with ultra-pure water for 15 minutes to remove any impurities present on the membrane surface. Afterwards, POME was fed to the ceramic membrane for 3 hours with operating conditions fixed at 400 ml/min flow rate (cross-flow velocity = 0.33 m/s) and 1 bar pressure. The permeation flux was obtained by recording the mass of filtered water at every 1-minute interval. The treated POME was then collected for sample analysis to investigate the rejection efficiency of the filtration process. The components of interest for rejection evaluation were turbidity and COD. Membrane flux was calculated as shown in Equation 1 and the rejection of components of interest (removal efficiency of membrane) was determined using Equation 2. The membrane filtration process was ended by cleaning the membrane in the sequence of ultra-pure water, sodium hydroxide, and ultra-pure water for 15-minute interval each. The experiment was then repeated with different sizes of ceramic membranes. For sequential study, the treated POME (permeate) of the previous membrane process was used as the feed for the subsequent membrane process. The arrangement of membrane sequences (as shown in Table 1) was adopted to observe the performance and fouling pattern of the integrated membrane system.

$$J = \frac{V}{At} \tag{1}$$

where J is the permeate flux ($Lm^{-2}h^{-1}$), V is the permeate volume (L), A is the membrane effective surface area (m^2), and t is the time taken to collect the permeate (h).

$$R = \left(\frac{C_i - C_f}{C_i} \right) \times 100\% \tag{2}$$

where R denotes the rejection efficiency of the foulant (%), C_i indicates the initial values of parameters (COD: mg/L, turbidity: NTU), and C_f indicates the final values of parameters (COD: mg/L, turbidity: NTU) after the filtration process.

For the evaluation of membrane cleaning efficiency, ceramic tubular membrane (0.2 µm) was selected (since no obvious difference in performance was observed among the three membranes). The cleaning procedure was started right after the POME filtration process with 0.5 M NaOH solution. After the tubular membrane was cleaned with NaOH, it was flushed with ultra-pure water to remove any chemical residue before POME filtration is resumed. The permeation flux was recorded and the filtered POME was collected for quality analysis. Similar cleaning protocol was conducted with another two chemical cleaning agents, 0.5 M KOH and 0.5 M HCl. The cleaning efficiency was represented by the restoration of flux (filtration with POME) after cleaning process.

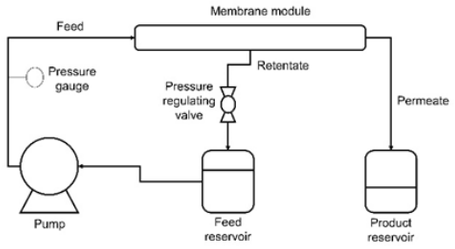

FIGURE 1. Experimental setup for POME filtration process

TABLE 1. Arrangement sequence of membrane units for filtration of POME

Sequential Filtration
A – B
A – C
B – C
A – B – C

A – tubular membrane (0.2 µm); B – tubular membrane (450 Da);
C – tubular membrane (200 Da)

ANALYTICAL METHODS

The turbidity of the samples before and after filtration was determined using Turbidimeter (2100N, HACH, USA). The COD was measured according to Standard Methods for the Examination of Water and Wastewater. The reagent used for COD measurement was purchased from HACH, USA. The samples before and after filtration were diluted into the desired concentration prior to further measurement. The diluted samples (2 ml) were then pipetted into a low range solution of COD reagent and further heated for 2 h in HACH DRB 200 reactor (HACH, USA) at 150 °C before being sent to HACH DR 3900 spectrophotometer (HACH, USA) for COD measurement.

RESULTS AND DISCUSSION

CHARACTERISTICS OF POME

The characteristics and appearance of POME before and after the filtration processes were tabulated in Table 2 and displayed in Figure 2. It can be observed that there was an obvious difference in color between the raw POME and treated POME. The untreated POME was brown in color while the color of the filtered POME gradually faded to pale yellowish, especially after the POME had undergone serial membrane treatment. The color of the samples reflected the presence of impurities (turbidity and COD) and efficiencies of the treatment processes. For comparison purpose, the allowable quality of the treated POME for discharge and reuse as boiler feed has also been included in Table 2 (Zainal et al. 2017; Ghani et al. 2018). It can be seen that the original anaerobically treated POME still contained high COD which made it unsuitable to be discharged directly. On the other hand, the quality of reclaimed water for reuse as boiler feed was more stringent with much lower turbidity and COD level. A first glance at the characteristics of filtered-POME indicated that the membrane processes managed to remove the turbidity to almost non-existent. However, the COD reduction was less effective. The reduction efficiencies of COD were displayed in Figure 3. The turbidity removal efficiencies were not presented as all the tubular membranes performed excellent in removing the turbidity of POME with up to 99.9%, regardless of either single or sequential treatment arrangement. This was clearly shown as almost no suspended particles were noticed in the treated POME (Figure 2). The high removal of turbidity could be translated to the rejection of suspended solids that are abundantly present in POME. Majority of the suspended solids in POME possessed a size distribution in the range of 0-5 μm, which were larger than the pore sizes of all three ceramic membranes (Fathilah 2015). Hence, it could be concluded that the removal of suspended solids by the tubular membranes was through size exclusion mechanism, where the larger particles were prevented to pass through the membranes with smaller pore sizes (Chen et al. 2019).

On the other hand, the reduction of COD did not show the similar trend of efficiency. Tubular ceramic membrane with the largest pore size (0.2 μm) recoded the lowest reduction efficiency at 13.5%, whereas the other two nanofiltration membranes (450 and 200 Da) achieved roughly the same reduction efficiencies (30-34%). This finding could be attributed to the differences in membrane pore size and the nature of impurities that contributed to COD. The huge difference between the removal efficiencies of turbidity and COD of all membranes shows that only a small portion of the COD was actually coming from the suspended organic particles, while majority of COD was originated from dissolved organic substances that are difficult to be removed by the tubular ceramic membranes. Due to the limitation of membrane pore size, dissolved organic substances have higher tendency to pass through the membrane and resulted in low removal efficiencies. Considering that tubular ceramic membrane (0.2 μm) possessed the largest pore size, the retention capability of organic substances was also the lowest. This observation trend was similar in other study where higher COD reduction efficiency was obtained for membranes with smaller pore size as they prevented the larger substances from penetrating through the membranes (Ko and Fan 2010).

In membrane processes that are dealing with high strength or highly polluted wastewater, the membrane unit

TABLE 2. Turbidity and COD of POME before/after membrane filtration, and allowable discharge limits and reuse as boiler feed

Treatment	Turbidity (NTU)	COD (mg/L)
None (raw POME)	57.00	5900
Allowable discharge limit	NA	100
Reuse as boiler feed	0-3	5
A	0.10	5100
B	0.09	4100
C	0.08	3900
A –B	0.07	3700
A – C	0.06	3300
B – C	0.05	3100
A – B – C	0.04	2900

A – tubular membrane (0.2 μm); B – tubular membrane (450 Da); C – tubular membrane (200 Da), NA – not applicable

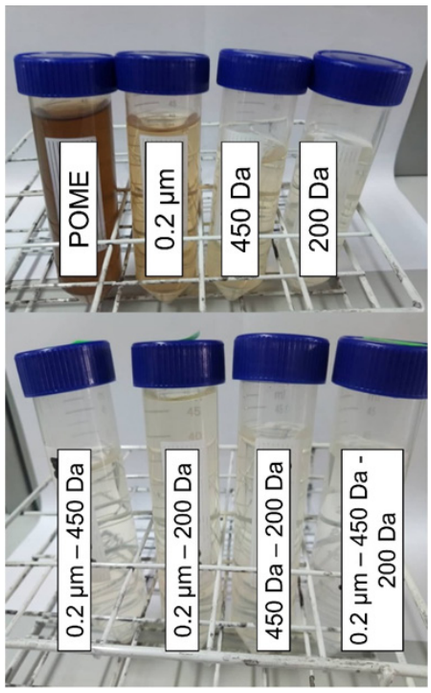

FIGURE 2. Physical observation of POME before and after the filtration of different membranes

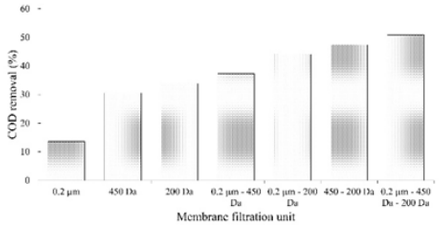

FIGURE 3. Removal efficiencies of COD by different membranes

will normally be integrated with another treatment process to further improve the overall treatment efficiency (Ang et al. 2014). In this study, sequential membrane treatment process was applied to investigate the improvement in terms of COD reduction. As can be seen from Figure 3, the presence of 0.2 µm membrane prior to 450 Da membrane only improved the reduction efficiency by 7%, while improvement of 10% was recorded for the 0.2 µm – 200 Da membrane treatment train. The combination of 450-200 Da membranes observed a removal efficiency increment of 13.5%, bringing the overall COD reduction to 47.5%. Lastly, the longest treatment train comprised of the three ceramic membranes recorded the highest COD reduction up to 51%. Overall, it can be seen that the integration of different membranes in the sequential treatment arrangement did not lead to much improvement in the removal of COD. This could be due to the size limitation of the ceramic membrane, where only a fixed portion of COD could be removed and the other substances could never be removed regardless of the extent of treatment unit. This finding is in agreement with the study reported by Ko et al. (2010) where the COD reduction from pulp and paper wastewater using ultrafiltration membrane was low (below 30%) due to the smaller molecular sizes of impurities (contributed to COD) that could penetrate through the membrane (Ko and Fan, 2010). These results showed that the combination of membranes in sequential treatment arrangement have to be properly investigated in order to truly harness the benefits while at the same time not increase the costing burden of the overall treatment process. Since the reduction of COD was not encouraging, the ceramic membranes might not be suitable for the reduction of COD. However, the high turbidity removal might prove to be useful as the removal of suspended solids may benefit the subsequent treatment process for COD removal (less interference from the suspended solids) such as advanced Fenton process and reverse osmosis membrane (Taha and Ibrahim 2014; Tabassum et al. 2015). Thus, tubular ceramic membrane (0.2 µm) was chosen for the cleaning study since turbidity was the impurity that could be effectively rejected and potentially retained on the membrane surface.

MEMBRANE PERFORMANCE AND FOULING

Figures 4 and 5 illustrate the flux profiles of the filtration processes using different types of membranes and sequences of ceramic membranes, respectively. Figure 4 displays a clear

different flux trends between 0.2 µm ceramic membrane and 450 Da and 200 Da membranes. The flux profile of 0.2 µm ceramic membrane declined gradually for the first hour of filtration and started to level off at 8-9 $L.m^{-2}.h^{-1}$. On the other hand, fluxes of 450 Da and 200 Da membranes did not record obvious decline and steadily fluctuated within the range of 7-8 and 4-5 $L.m^{-2}.h^{-1}$, respectively. The variation in flux profiles could be attributed to the initial flux values of the membranes during the starting of filtration period. The initial fluxes for 0.2 µm, 450 Da, and 200 Da membranes were 16, 7, and 5 $L.m^{-2}.h^{-1}$, respectively. The much higher initial flux of 0.2 µm membrane indicated a higher permeation drag that led to the fast cover-up of the membrane surface by foulants. Subsequently, the available passage of water would be reduced significantly and hence resulted in sharp flux decline right after the start of filtration process. This observation was inconsistent with other reported studies where higher initial flux (representing larger permeation drag) would introduce more foulants to the membrane surface by convection and back diffusion of those foulants to the bulk would be weakened (Ang et al. 2016). The deposition and accumulation of foulants on the membrane surface would form a cake layer that imposed additional resistance for water passage and led to flux decline. The mild flux decline of 450 Da and 200 Da membranes was probably due to its much lower flux where equilibrium between the foulants retained on the membrane surface and back diffusion to the bulk has been achieved (Wang and Tang 2011).

Apart from permeation drag, another factor that resulted in flux decline for 0.2 µm membrane was the blocking of membrane pores. As previously mentioned, POME consists of suspended particles that may deposit on the membrane surface (for impurities with large molecular weight/size). The formation of cake layer is normally considered as reversible fouling, where it can be removed by cleaning. However, the small-size or low molecular weight suspended solids have a greater chance to enter the membrane pores and block the passage of water in the membrane layer (Ly et al. 2019). Consequently, membrane flux would be reduced as the pathway for water permeation has been occupied by these impurities. This phenomenon was more prevalent for 0.2 µm membrane since it possessed a larger pore size. The smaller pore size of 450 Da and 200 Da membranes prevented the particles from getting into the pores and clogged them.

Figure 5 presents the flux profiles of the last membrane in each of the sequential filtration processes. Severe flux decline trend as in the previous figure was not present in this case. This could be due to lower amount of impurities being fed to the membrane as the pretreatment filtration processes have removed most of the foulants (Table 2) and the low flux of 450 Da and 200 Da membranes that resulted in lower fouling propensity (as explained in the previous paragraph). The presence of 0.2 µm or 450 Da membranes as the pretreatment prior to 450 Da or 200 Da membranes have elevated the permeation flux of the last membrane filtration unit of the treatment train. The fluxes of the four treatment trains were around 15, 14, 13, and 9 $L.m^{-2}.h^{-1}$, corresponding to the experimental sets 0.2 µm – 450 Da, 0.2 µm – 200 Da, 450 Da – 200 Da, and 0.2 µm – 450 Da – 200 Da, respectively. With the removal of more than 99% of turbidity in POME, the fluxes of 450 Da and 200 Da membranes have been increased 2-3 fold of original flux without pre-treatment (Figure 4). This signifies the need to have pretreatment process prior the tighter membranes in order to utilize its high rejection property while achieving higher flux (Lee et al. 2016).

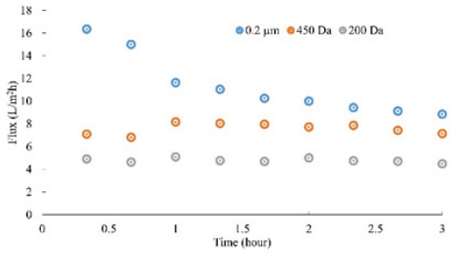

FIGURE 4. Membrane permeate flux for single stage membrane treatment process

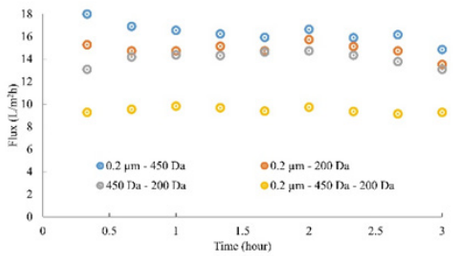

FIGURE 5. Membrane permeate flux for sequential membrane treatment process
(data presented was referring to the flux of the last stage membrane)

TABLE 3. Flux recovery of 0.2 µm membrane after cleaning with different media

Cleaning media	Recovery (%)
Ultra-pure water	50
HCl	83
NaOH	83
KOH	77

MEMBRANE CLEANING EFFICIENCY

Table 3 presents the flux recovery of 0.2 µm membrane after cleaning with different media. A general view of the recovery values indicates that cleaning using chemicals (HCl, NaOH, and KOH) resulted in better recoverability with the initial flux recovered up to 77-80% as compared to cleaning using ultra-pure water with flux recoverability of 50% only. This could be attributed to the interaction between the cleaning agents with foulants deposited on the membrane surface or present in the membrane pores. As mentioned in other studies, cleaning with ultra-pure water normally can remove the impurities that loosely deposited or attached on the membrane surface (Martí-Calatayud et al. 2018). The removal of foulants was mostly due to the shear force aroused from the backwashing. However, if the foulants formed a compact layer on the membrane surface, cleaning using ultra-pure water might be inefficient in removing the foulants. In this context, it can be said that ultra-pure water was inappropriate medium for the cleaning as the recovered flux was actually close to the flux level before the cleaning process (as shown in Figure 4 where the stabilized flux for 0.2 µm membrane was half of the initial flux), indicating inefficient cleaning. Consequently, this cleaning approach is inefficient in removing the persistent foulants that have adsorbed or interacted with the membrane either on the surface or in the pores.

The bonding or interaction between the foulants and membrane has to be broken in order to have a better chance in removing the foulants. Zhao et al. (2018) reported that NaOH could reduce the adhesion force between the foulants and the membrane surface, freeing the organic foulants and recovering the membrane flux (Zhao et al. 2018). In this case, the alkalis (KOH and NaOH) could initiate hydrolysis reaction for the proteins and polysaccharides (components of POME) trapped by the membrane wherein the hydrogen group was removed from the compounds and replaced by the salt. Subsequently, the foulants would be freed from the membrane and removed during cleaning process (Alresheedi et al. 2019). Surprisingly, cleaning with HCl resulted in flux recoverability as good as cleaning with alkalis and in agreement with past literature (Ali Amat et al. 2015). Normally, chemical cleaning with acid is associated with removal of inorganic material (Regula et al. 2014). Though POME is known for its large amount of organic substances, it also contains a considerable amount of nutrients (phosphorus, nitrogen, and potassium). The retention of nutrients on the membrane surface may lead to precipitation (scales) that also contributed to membrane blockage and flux decline. After cleaning with HCl, the precipitates would be dissolved and made way for water permeation. Another possible explanation for high flux recoverability of HCl cleaning was the destabilization of foulants under acidic condition, which has been reported by Kim et al. (2020) where the silica colloids were prevented from forming agglomerates owing to the short-range strong repulsive hydration forces at low pH (Kim et al. 2020). The incomplete recoverability of all cleaning implies that some of the impurities were still present in the membrane. This observation was probably due to the pore sizes of 0.2 µm ceramic membrane that was large enough for the foulants to enter and clog the membrane pores. Similar observation was reported by Zhang et al. (2013) where small sized organic molecules could penetrate deeply into membrane pores and layer, which increased the resistance of backwashing and cut down the efficiency of cleaning process (Zhang et al. 2013).

CONCLUSION

All ceramic membranes showed more than 99% removal efficiencies of suspended solids (turbidity) present in POME. The removal of the turbidity could be attributed to size exclusion mechanism, where the larger particles were retained by the membrane from passing through the membranes. However, the removal of COD was ineffective as the dissolved organic substances that contributed to COD were able to pass through the membranes. The sequential membrane treatment comprising the longest treatment train (0.2 µm – 450 Da – 200 Da) was only able to remove 51% of COD. This indicates that the ceramic membranes were suitable for removing turbidity but the removal of COD has to be done by other treatment technologies. The plus side is that the ceramic membranes could remove the turbidity such that the treated POME is of better quality for subsequent treatment. The membrane flux patterns indicate that higher flux (0.2 µm) resulted in moderate flux decline, where the larger permeation rate brought more impurities and blocked the membrane surface for water passage in a short duration period. Chemical cleaning was more efficient as compared to physical cleaning with ultra-pure water. This could be because the interaction between foulants and membrane surface has been disrupted and subsequently freed from blocking the membrane surface. However, the membrane flux was not fully recovered, though the stabilized flux remained almost the same. This could be a sign that some of the small-size impurities might still persist in the membrane

but when equilibrium between the convection of foulants to membrane surface and back-diffusion to the bulk solution has been achieved, the stabilized flux would be the same as before cleaning.

DECLARATION OF COMPETING INTEREST

None.

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