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Reduction of Total Suspended Solids, Turbidity and Colour of Palm Oil Mill Effluent using Hybrid Coagulation-Fltrafiltration Process

W. Q. Ng, S. O. Lai*, K. C. Chong, S. S. Lee, C. H. Koo & W. C. Chong

Department of Chemical Engineering, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 43000 Kajang, Selangor, Malaysia

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ABSTRACT

High consumption and production of palm oil have led to the massive generation of palm oil mill effluent (POME). This study was intended to reduce the total suspended solids (TSS), turbidity and colour using hybrid coagulation-ultrafiltration process. POME was pre-treated with coagulation process using polyaluminium chloride (PAC) and optimization of operating condition for coagulation process was performed. The coagulation results revealed that optimum pH, dosage of coagulant and rapid mixing speed were pH 4, 600 mg/L and 200 rpm, respectively. It achieved the highest percent reduction of TSS, turbidity and colour with 99.74%, 94.44% and 94.60%, respectively. Ultrafiltration (UF) membrane was fabricated using polyethersulfone (PES), polyvinylpyrrolidone (PVP) and titanium dioxide (TiO_2) nanoparticle. Different concentrations ranging from zero and 1.0 wt% of TiO_2 nanoparticles were added into the dope solution. The characterization studies of UF membranes confirmed that higher concentration of TiO_2 provided higher pure water permeability and more porous structure in the UF membranes. The amount of TiO_2 in membrane only affected the permeate flux but had no obvious effects on the reduction of TSS, turbidity and colour. The optimum transmembrane pressure was found to be 3 bar, resulting in the greatest reduction of TSS, turbidity and colour.

Keywords: Palm oil mill effluent, coagulation-ultrafiltration, TDS, colour

1.0 INTRODUCTION

Palm oil is a vegetable oil that is widely consumed around the world and this increases the production of palm oil significantly. However, voluminous amount of water is required to produce palm oil and therefore huge amount of oily wastewater is created. This oily wastewater is known as palm oil mill effluent (POME). POME, an effluent which is viscous and consists of large amount of colloidal suspension [1]. Raw POME contains large portion of water up to 95 - 96 %, 0.6 – 0.7 % oil and 4 – 5 % total solids [2]. High organic matter content and suspended solids found in POME leads to high turbidity and colour in the solution. Direct discharge of POME into water stream creates a huge impact to both environment and human health. POME characteristics are presented in Table 1.

Malaysia, as one of the developing countries, has experienced high industrial development and becomes one of the biggest palm oil manufacturers and exporters in the world. High production rate of palm oil has resulted in the discharge of high amount of effluents. There are about 53 million m^3 of palm oil mill effluent (POME) being produced annually in Malaysia [3].

* Corresponding to: S. O. Lai (email: laiso@utar.edu.my)
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Table 1 Characteristics of palm oil mill effluent

Parameters	Concentration	Units	Ref
pH	4	-	[4]
Oil and Grease	6,000	mg/L	[4]
Biochemical Oxygen Demand , BOD_3	25,000	mg/L	[4]
Chemical Oxygen Demand, COD	50,000	mg/L	[4]
Total Solids	40,000	mg/L	[4]
Total Suspended Solids	18,000	mg/L	[4]
Volatile Solids	34,000	mg/L	[4]
Ammoniacal Nitrogen	35	mg/L	[4]
Total Nitrogen	750	mg/L	[4]
Turbidity	11,000	NTU	[5]
Colour	10,000	ADMI	[6]

Throughout the past few decades, plenty of methods such as adsorption, coagulation, flocculation, electro-coagulation and flotation have been developed to treat POME [5]. Among all the developed methods, biological treatments are commonly used by palm oil mill management to treat POME [7]. It utilizes bacteria to decompose organic matters into different products [8]. However, biological treatment system is not ideal due to the high cost and generation of biogas that is corrosive and odorous [8]. Thus, membrane filtration process is used to treat POME as it is found to be more economically feasible and effective in removal of total suspended solids, turbidity and colour but it suffers severe fouling problem. Therefore, a combination of coagulation and membrane separation technology is utilized to reduce the fouling problem and to achieve better performance in treatment.

Coagulation refers to the chemical process which neutralizes or reduces the electric charge on suspended solids. In the effluent, small particles that have the identical charges causes particles to repel each other, and thus leading to non-settable particles. By introducing coagulants into the effluent, destabilization of colloidal particles is able to achieve. The neutralization of negative charges introduces Van der Waals force of attraction [9]. As a result, small particles aggregates into microflocs making it easier to be settled and removed, and hence diminishing fouling problem in membranes.

The efficiency of coagulation process is significantly influenced by several factors which includes the type and dosage of coagulants, pH, mixing speed and time [10]. Optimization of these factors provides a high efficiency of treatment [11]. The efficiency of coagulants is highly dependent on the pH of solutions. Therefore, pH adjustment has to be performed before proceeding to coagulation process. Ahmad [5] found that coagulation using PAC exhibited the highest rejection of total suspended solids at pH 4.5. Using PAC at highly acidic condition causes aluminium cations to exist in significant amount leading to the destabilization of suspended solids. Ahmad [5] also stated that coagulation using PAC at pH higher than 5 decreased the rejection of total suspended solids and turbidity. Besides, Teh [12] also reviewed that the coagulation performance decreased when coagulation was performed outside the effective pH range due to the re-stabilization of colloids. However, Farajnezhad and Gharbani [13] reported that the effect of pH for coagulation was insignificant when PAC was used to treat effluent from petroleum industry. Generally,

insufficient or excessive dosage of coagulants will lead to poor performance in coagulation process. Excessive dosage of coagulants causes the agitation of sedimentation process which will result in resuspension of aggregated particles. Similarly, Ahmad [5] also found out that having a higher dosage of coagulant than the optimum amount leads to re-stabilization of colloids which can be observed from the increase of suspended solids reading.

Rapid mixing is an important step in coagulation process which allows the dispersion of coagulants in the solution. Sufficient mixing speed allows high dispersion of coagulants and thus leading to higher effective collision between colloids. Increasing the rapid mixing speed higher than optimum may cause high shear forces in the solution, and thus breaking the flocs formed. However, high shear forces do not always break aggregates but re-organize particles composing flocs, and hence making it more compact [14].

In membrane separation technology, a special porous material that has an interception role is used to remove contaminants physically [15]. In this study, ultrafiltration was studied where molecules are separated depending on size of molecules by a sieving effect. Membrane filtration often suffers from membrane fouling problem whereby utilizing hybrid system improves the fouling problem and increases the lifespan of the membrane. Besides, higher removal efficiency can also be achieved through hybrid membrane process [16].

In this study, a hybrid coagulation-ultrafiltration process was utilized to reduce the total suspended solids, turbidity and colour in anaerobically treated POME. Coagulation process was implemented as pre-treatment step before ultrafiltration to reduce total suspended solids, turbidity and colour in the anaerobically treated POME. It allows higher retention of water-soluble substances and contaminants, and thus reducing membrane fouling problem [17]. Optimal operating conditions for coagulation process using polyaluminium chloride (PAC) to remove total suspended solids, turbidity, and colour from anaerobically treated POME were determined. Different concentration of titanium dioxide were into membranes and various transmembrane pressure were applied to study the effects on permeate flux and reduction of total suspended solids, turbidity and colour.

2.0 METHODS

2.1 Materials

Anaerobic treated palm oil mill effluent produced by a local palm oil mill located in Sri Jaya, Pahang was obtained from i-Chem Solutions Sdn Bhd. Polyaluminium chloride (PAC) as coagulant was supplied by Chemnergy Enterprise Sdn Bhd. Concentrated hydrochloric acid and sodium hydroxide were purchased from Merck. Besides, polyethersulfone (PES) was selected to be the base for polymeric membrane, whereas N-methylpyrrolidinone (NMP) as a solvent was purchased from Merck. Furthermore, polyvinylpyrrolidone (PVP) and titanium dioxide (TiO_2) were purchased from Sigma Aldrich.

2.2 Preparation of Membranes

Different compositions of dope solution were prepared for the fabrication of ultrafiltration (UF) membranes.

Table 2 Compositions of dope solution for ultrafiltration membranes

Membrane	PES (wt%)	TiO_2 (wt%)	PVP (wt%)	NMP (wt%)
U1	16.0	-	1.0	83.0
U2	16.0	0.1	1.0	82.9
U3	16.0	0.5	1.0	82.5
U4	16.0	1.0	1.0	82.0

Table 2 summarises different compositions of dope solution. The PES composition for all UF membrane were set at 16 % with 1 % of PVP. Different amounts of TiO_2 nanoparticles were added into U2 – U4. NMP solvent took up the rest of the composition percentage. Moisture content in PES pellets was first removed by drying it using an oven at 60°C for 24 hours. Then, PES pellets were added into the NMP solvent and stirred at the speed of 600 rpm until all the pellets were dissolved. Pre-weighted TiO_2 nanoparticles and PVP were added once to produce the dope solution. The dope solution was sonicated using an ultrasonic cleaner (SK5200GT, KUDOS) to ensure all the additives were completely dispersed in the dope solution and to remove any additional air bubbles in the dope solution.

Phase inversion technique was used to prepare all the membrane. Firstly, the dope solution was applied onto a clean and smooth glass plate. Then, a hand casting knife was used to spread the dope solution evenly on glass plate. The casting thickness of the membrane was 250 µm. The glass plate was placed into a distilled water bath to allow the formation of membrane through solvent-nonsolvent exchange.

2.3 Membrane Characterizations

The UF membranes was characterised to understand their physiochemical properties. Scanning electron microscopy (S-3400N, Hitachi) was used view the cross sectional morphology of the membranes. Energy-dispersive X-ray Spectroscopy (EDX) was used to determine the components that exists in all the fabricated membranes. Fourier Transform Infrared spectroscopy (IS10, NICOLET) was used to identify the functional groups on the fabricated membranes.

The porosity of the membranes was calculated using Equation 1.

$$\varepsilon = \frac{\frac{w_w - w_d}{\rho_w}}{\frac{(w_w - w_d)}{\rho_w} + \frac{w_d}{\rho_m}} \quad (1)$$

where w_w is the wet weight of membrane; w_d is the dry weight of membranes; ρ_w is the density of water; ρ_m is the density of membrane. The pore size distribution of the membranes was determined using Equation 2.

$$r_m = \sqrt{\frac{(2.9 - 1.75\varepsilon)8\eta l Q}{\varepsilon A \Delta P}} \quad (2)$$

where η is the water viscosity at 25 °C; l is the membrane thickness; Q is the volume of the permeate water per unit time; A is the effective area of the membrane; ΔP is the operational pressure. Pure water permeability of the fabricated membranes was measured using Equation 3.

$$J_w = \frac{V}{A \times \Delta t} \quad (3)$$

where Jw is the pure water flux; V is the volume of distilled water; A is the

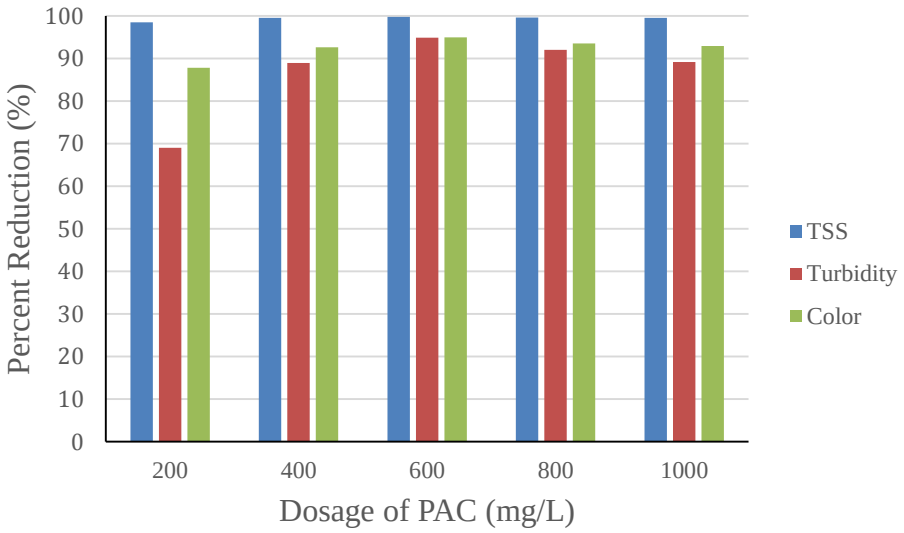

Figure 1 Percent Reduction for Total Suspended Solids, Turbidity and Colour at Different Coagulant Dosage under pH 4.5 and 150 rpm Rapid Mixing Speed

effective membrane area; Δt is the sampling time.

2.4 Experimental Procedure

2.4.1 Coagulation of POME

Anaerobic treated palm Oil Mill Effluent (POME) was subjected to coagulation process using polyaluminium chloride (PAC) as coagulant prior to membrane filtration process. The coagulation process was carried out using a flocculation test unit (LS-260001-A). The pH of POME solution was first adjusted using concentrated HCl or sodium hydroxide. PAC was then added into the pH-adjusted POME for coagulation. The mixing of POME solution was carried out using rapid mix and slower mix. Durations for rapid mix and slower mix were fixed at 1 and 30 minutes, respectively. The coagulated samples were removed from the flocculation test unit and allowed to settle for 60 minutes. The pH, coagulant dosage and rapid mixing speed were optimized for the best reduction of total suspended solids, turbidity and colour from the anaerobically treated POME.

2.4.2 Membrane Filtration

A dead end filtration unit was required in this study. The system was pressurized using N_2 gas and the feed solution was continuously injected into the stirrer cell to produce permeate. The transmembrane pressure (TMP) was varied in this experiment and the permeate flux was calculated. The fabricated membranes were subjected to different TMP (2 – 5 bar) to investigate the effect of TMP on permeate flux and reduction of total suspended solids, turbidity and colour. The permeate flux was determined using Equation 3 by replacing the volume of distilled water with volume of permeates.

The total suspended solids of all coagulated samples and membrane filtered products were determined using a spectrophotometer (HACH DR 3900). The percentage of reduction was calculated using Equation 4.

$$R = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \qquad (4)$$

where C_p is the concentration in permeate and C_f is the concentration in feed solution.

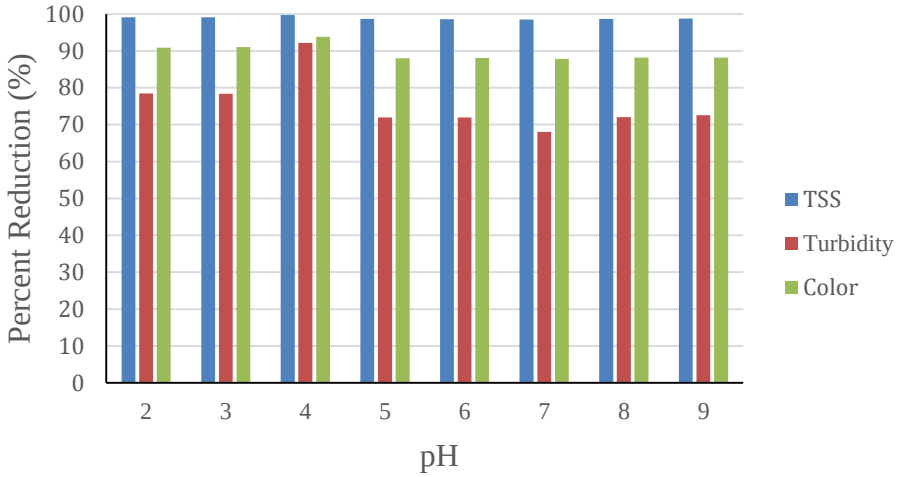

Figure 2 Percent Reduction for Total Suspended Solids, Turbidity and Colour at different pH under 600 mg/L coagulant dosage and 150 rpm rapid mixing speed

The determination of colour was also carried out using a spectrophotometer. The colour of solutions were measured in American Dye Manufacturers Institute (ADMI) unit. The percentage of colour reduction was evaluated using Equation 5.

$$R = \left(1 - \frac{ADMI_p}{ADMI_f}\right) \times 100\% \qquad (5)$$

where $ADMI_p$ the colour in permeate; $ADMI_f$ is the colour in feed solution.

The turbidity of different POME samples was measured using a turbidity meter (TN-100, Eutech Instruments) in Nephelometric Turbidity Units (NTU). The percentage of reduction was evaluated using Equation 6.

$$R = \left(1 - \frac{NTU_p}{NTU_f}\right) \times 100\% \qquad (6)$$

where NTU_p is the turbidity in permeate; NTU_f is the turbidity in feed solution.

3.0 RESULTS AND DISCUSSION

3.1 Optimization of Operating

3.1.1 Optimum PAC dosage

The effect of PAC dosage to TSS, turbidity and colour of POME is demonstrated in Figure 1. The percent reduction of TSS, turbidity and colour were reduced with increasing of PAC dosage, but start to reduce when the dosage of PAC beyond 600 mg/L. At dosage below 600 mg/L, the percent reduction is low due to insufficient amount of coagulant, resulting in inadequate of adsorption sites in coagulant, restrict the bridge formation between adjacent particles and re-stabilization of colloid particles [12]. At dosage beyond 600 mg/L, the percent reduction was reduced as it beyond critical coagulation dosage. High PAC dosage lead to re-stabilization of counter ion, resulting in dispersion of flocs, which restrict the settling of particles [18].

3.1.2 Optimum pH condition

Coagulation process is highly sensitive to pH condition of solutions as it will affect the charges of the particles. The

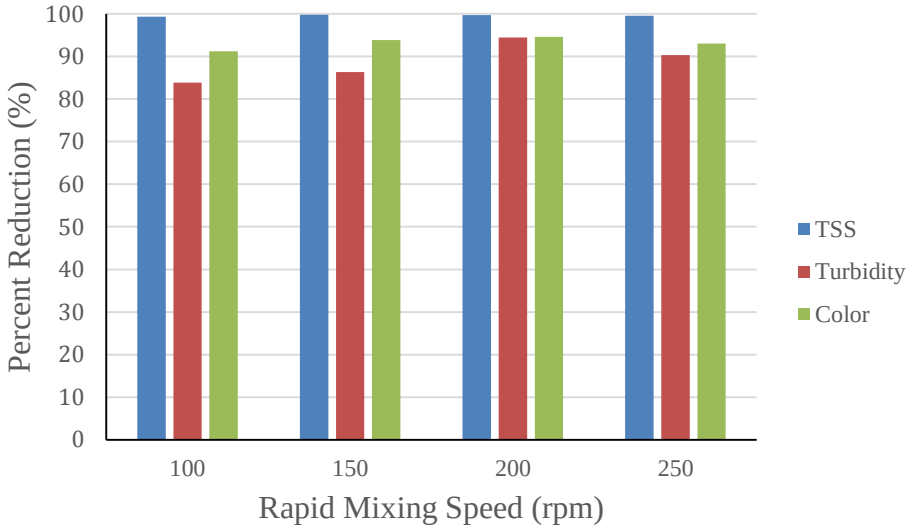

Figure 3 Percent Reduction for Total Suspended Solids, Turbidity and Colour at Different Rapid Mixing Speed under pH 4 and 600 mg/L Coagulant Dosage

effect of solution pH on TSS, turbidity and colour were studied and illustrated in Figure 2. Percent reduction of TSS, turbidity and colour at pH 4 were the highest among the pH range. The percent reduction of total suspended solids, turbidity and colour at pH 4 were 99.67%, 92.19% and 93.85%, respectively.

The optimum pH for coagulation is pH 4. This result is supported by Ahmad [5] who reported the PAC had better performance at mild acidic condition. The addition of acid reduces the surface charges, and hence eliminating the inter-particle forces and promoting electrostatic attraction which enhanced the destabilization of colloid particles [12].

For aluminium based coagulant, high amount of positively charge aluminium cation exists in lower pH effluent which creates a favourable condition for charge neutralization to occur [12]. However, the performance of PAC in reduction of turbidity and colour decreased significantly when the pH of POME was set at 5 and above. This is due to the re-stabilization of colloids particles as the coagulation process was conducted beyond effective pH range which is consistent with the findings reported by Teh [12].

3.1.3 Optimum Rapid Mixing Speed

Rapid mixing speed has a great impact on the coagulation process as it will greatly affect the size of flocs. The effect of mixing speed was studied and demonstrated in Figure 3. The optimum rapid mixing speed is 200 rpm at condition of pH 4 and 600 mg/L coagulant dosage. The percent reduction for TSS, turbidity and colour were 99.74%, 94.44% and 94.60%, respectively. The percent reduction is increased with increasing of rapid mixing speed. It starts to decreases at the saturation point of 200 rpm. This is due to lower rapid mixing speed offered a lower particle collision rate, and thus decreasing the flocs formation rates and resulting in poorer performance of coagulation process. Besides, rapid mixing speed above 200 rpm generates high shear force which will cause primary particles forming the flocs to be unable to aggregate.

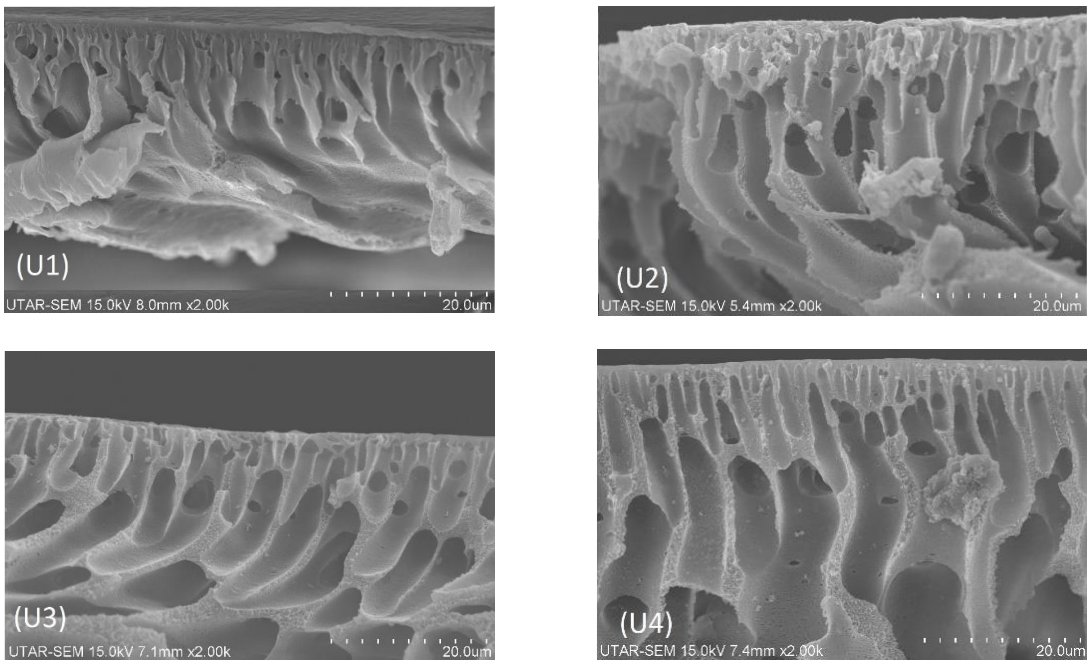

Figure 4 SEM Micrographs of Cross-Sectional Structure for Membranes U1, U2, U3 and U4 at Magnification of 2000x

Thus, bigger size of flocs unable to form at high rapid mixing speed.

3.2 Membrane Characterization

3.2.1 Cross-sectional Morphology

Figure 4 illustrates the cross-sectional structure for all 4 different membranes which were U1, U2, U3 and U4. Generally, a dense top layer and porous support layer were noticed in all fabricated membranes. Membrane U1 showed a more compact top layer when compared to other membranes. This was due to the slower diffusion rate between solvent to non-solvent during phase inversion. Dope solution without nanoparticles created a stronger affinity, leading to a lower demixing (solidification) rate [19].

For membranes U2, U3 and U4, TiO_2 nanoparticles were added to modify the morphology of the membrane. The addition of TiO_2 nanoparticles increased rate of mass transfer between solvent to non-solvent during the phase inversion process as it provided a high specific area and good hydrophilicity which will increase the diffusion rate of dope solution during phase inversion [20]. Thus, membranes U2 to U4 showed an increasing size of finger-like macroporous structure.

3.2.3 Energy Dispersive X-ray Spectroscopy (EDX)

The results and images of EDX are illustrated in Table 3 and Figure 5. It could be seen that the TiO_2 nanoparticles were successfully incorporated into the membrane matrix and the amount of nanoparticles increased across the membranes. The chemical composition of polyethersulfone (PES) contributed to the presence of carbon (C), oxygen (O) and sulphur (S) composition in the matrix of membranes.

Table 3 Weight Percent (wt%) of Membranes

	U1	U2	U3	U4
C	61.16	62.08	60.19	57.05
O	29.70	22.56	30.65	22.96
S	9.14	14.89	8.51	16.19
Ti	0.00	0.46	0.65	3.80

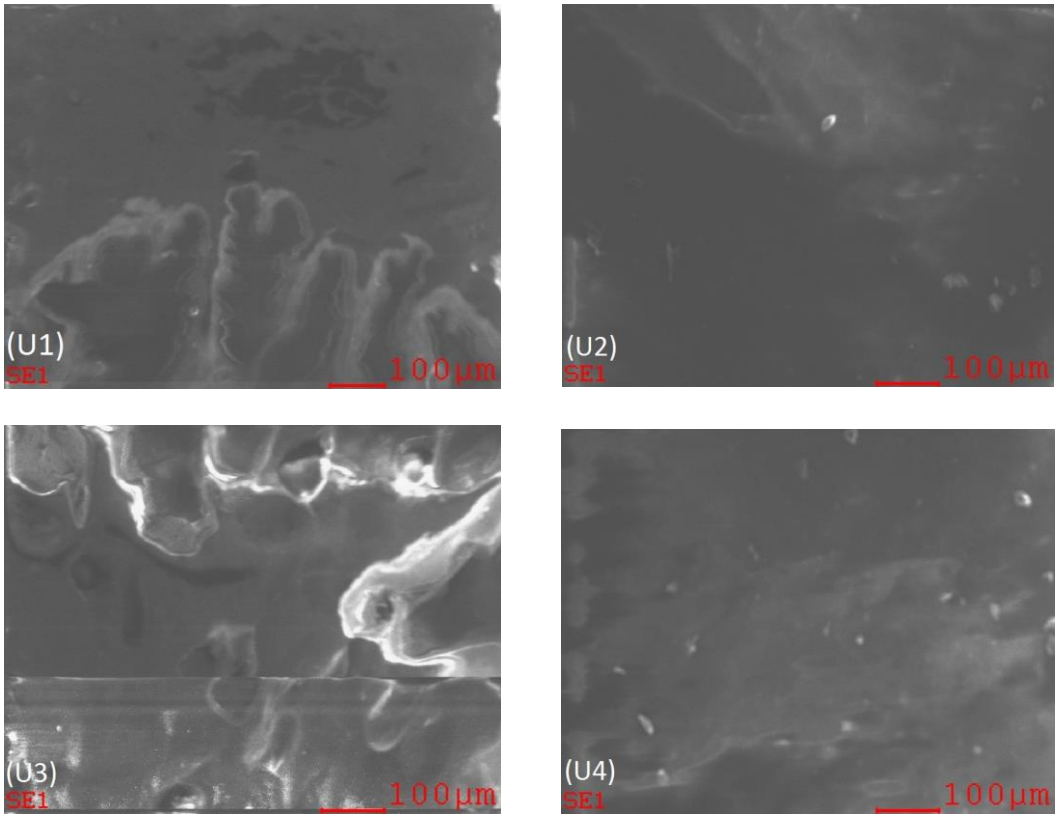

Figure 5 EDX Images of Surface for Membranes U1, U2, U3 and U4

3.2.3 Porosity and Pore Size Distribution

The porosity and pore size was highly affected by the diffusion rate of solvent in the phase inversion stage. Based on Table 4, it was observed that the porosity of membranes increased from membranes U1 to U4. By comparing membranes U1 and U2, the porosity of membrane U2 increased owing to the addition of TiO_2 nanoparticles. Membrane U4 with the highest amount of TiO_2 possessed the highest porosity of 0.8958. The hydrophilic properties of TiO_2 accelerated the diffusion rate between solvent and non-solvent, and thus promoting the membrane formation. Therefore, the addition of TiO_2 nanoparticles improved the porosity of membranes thus enhanced the hydrophilicity of membranes.

The pore size of membranes is also tabulated in Table 4. As the loading of TiO_2 increased, the pore size of membranes also increased. Membrane U4 exhibited the largest pore size among other membranes due to the highest amount of nanoparticles added. The addition of nanoparticles reduced the affinity of dope solution causing faster demixing (solification) to occur, and eventually resulting in large pore size. A strong affinity led to delayed demixing, and formation of smaller pore size [21].

Table 4 Porosity and Pore Size of Membranes

Membrane	Porosity (%)	Pore size (µm)
U1	85.26	0.071
U2	87.67	0076
U3	89.26	0.082
U4	89.58	0.091

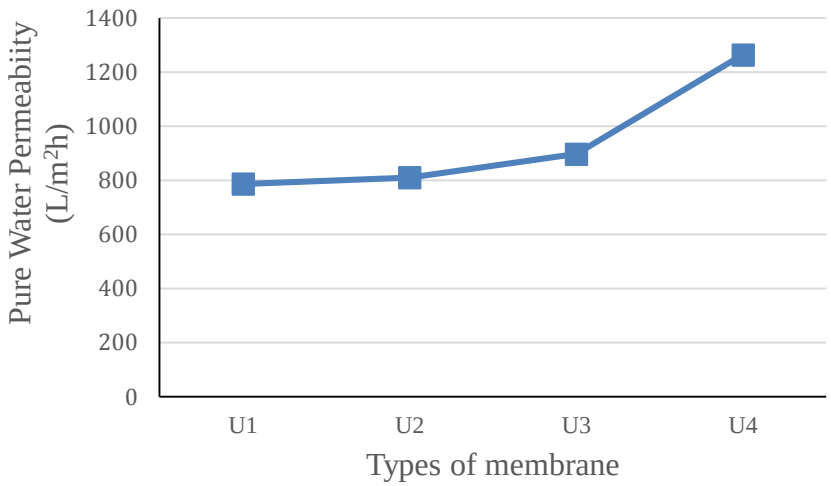

Figure 6 Pure Water Permeability of Membranes under Transmembrane Pressure of 1 bar

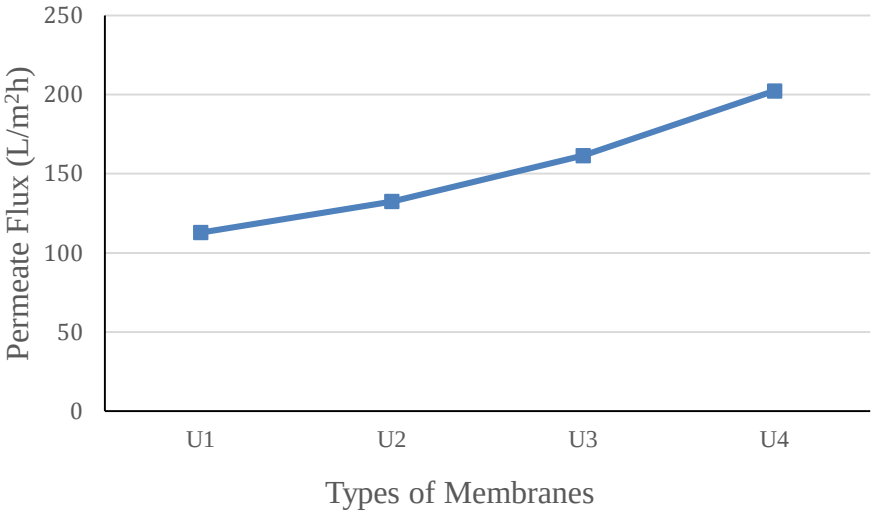

Figure 7 Permeate Flux for Different Types of Membranes under Transmembrane Pressure of 3 bar

3.3 Membrane Filtration

3.3.1 Effect of TiO_2 Loading on Pure Water Permeability and Permeate Flux

Figure 6 presents the pure water permeability results for different membranes. The pure water permeability of membranes was observed to demonstrate an increasing trend with the higher amount TiO_2 nanoparticles added into the membranes in Figure 6. The addition of TiO_2 nanoparticles increased the pore size and porosity of membranes, and therefore promoting the permeation of water. However, low amount of TiO_2 nanoparticles have insignificant effect to the pure water permeability of membrane as depicted by membrane U2. The addition of 0.1% of TiO_2, however, did not promote the pure water permeability of membrane, but it was shown to have a relatively higher pure water permeability in membranes U3 and U4 due to higher amount of TiO_2 nanoparticles added. This finding was found to be consistent with the

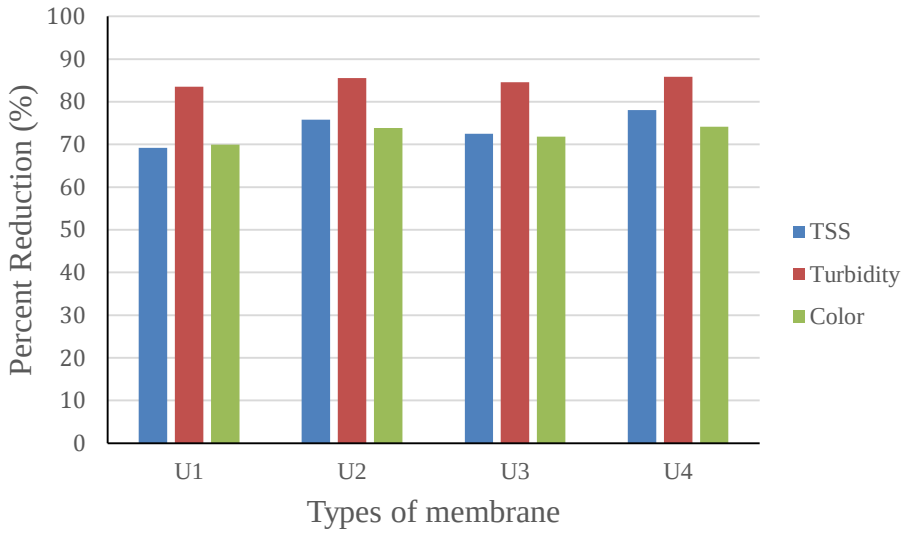

Figure 8 Percent Reduction of Total Suspended Solids, Turbidity and Colour for Different Types of Membranes under Transmembrane Pressure of 3 bar

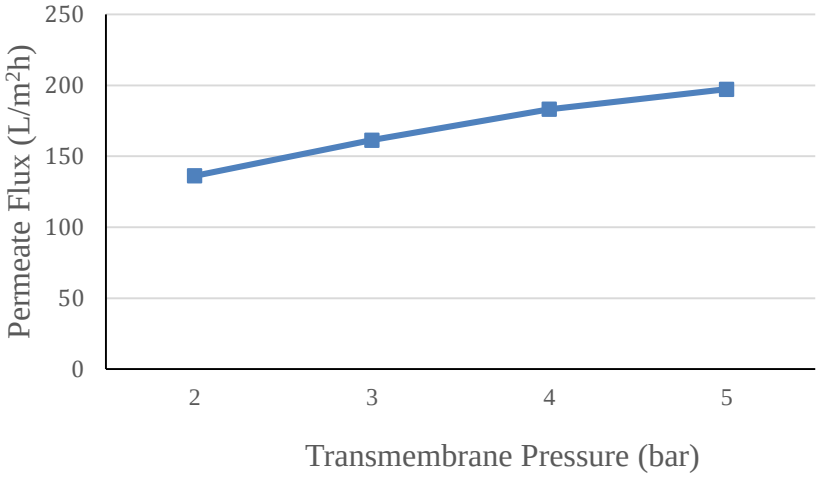

Figure 9 Permeate Flux for Membrane U3 at Different Transmembrane Pressures

permeate flux of membranes. The permeate flux for different membranes under TMP of 3 bar is presented in Figure 7. It was observed that the permeate flux increased across membranes as the concentration of TiO_2 nanoparticles increased.

3.3.2 Effect of TiO_2 Loading on Reduction of Total Suspended Solids, Turbidity and Colour

Based on Figure 8, U4 had the highest percent reduction of TSS, turbidity and colour. The percent reduction of TSS, turbidity and colour were 78.00%, 85.81% and 74.12%, respectively. However, the effects of TiO_2 loading on reduction of TSS, turbidity and colour were studied by comparing the reduction by other membranes. It was observed that the percent reduction by other membranes did not show any significant changes, indicating that the increased loading of TiO_2 did not give a higher reduction in TSS, turbidity and colour. The addition of low TiO_2 nanoparticles concentration in

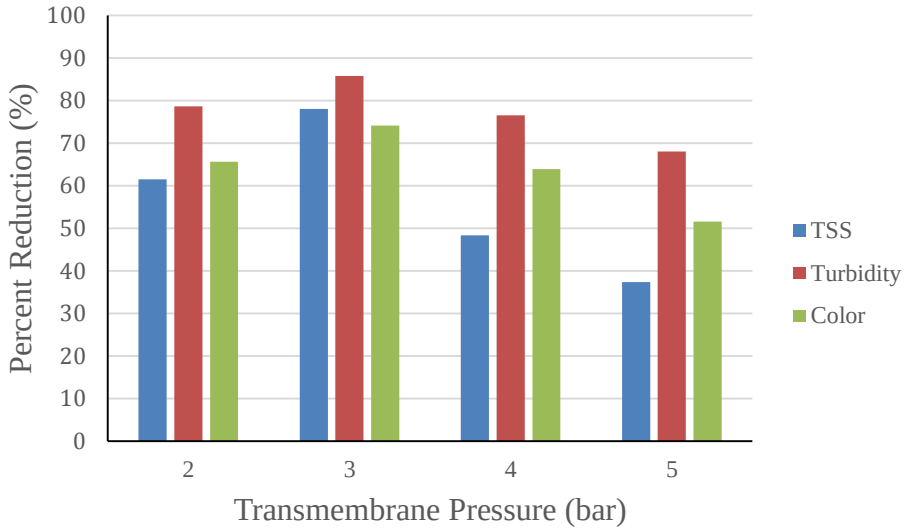

Figure 10 Percent Reduction of Total Suspended Solids, Turbidity and Colour for Membrane U4 under Different Transmembrane Pressures

membrane resulted in insignificant effect in the reduction of TSS, turbidity and colour. Hence, it could be concluded that the addition of low TiO_2 concentration only increased permeate flux, but not improve the reduction of TSS, turbidity and colour, although surface modification was made.

3.3.3 Effect of Transmembrane Pressure on Permeate Flux

Figure 9 depicts the permeate flux for membrane U3 at different TMPs. The results showed that the permeate flux for the membrane increased accordingly with higher TMP. With higher TMP, higher forces were exerted onto the membrane to allow the flux to increase. Therefore, it could be summarized that that higher TMP would give a greater permeate flux. However, TMP applied onto the membrane should not exceed the mechanical strength of membrane which would cause rupture of membrane, leading to low separation efficiency.

3.3.4 Effect of Transmembrane Pressure on Reduction of Total Suspended Solids, Turbidity and Colour

Based on Figure 10, the reduction of TSS, turbidity and colour presented an increasing trend and deceases after applying TMP of 4 bar. It was found that the optimum TMP for the reduction of TSS, turbidity and colour for membrane U4 was at 3 bar as it achieved the highest percent reduction. The percent reduction for TSS, turbidity and colour were 78.02%, 85.81% and 74.12%, respectively. Applying TMP greater than 4 bar experienced a significant drop in percent reduction due to the high TMP force exerted onto the membrane causing solid particles to rapidly pass through the membrane, and hence creating a lower percent reduction. Greater TMP caused more particles to force through the membrane without separation, leading to even lower percent reduction. This can be seen from the percent reduction TMP of 5 bar as it had a lower percent reduction compared to that at TMP of 4 bar.

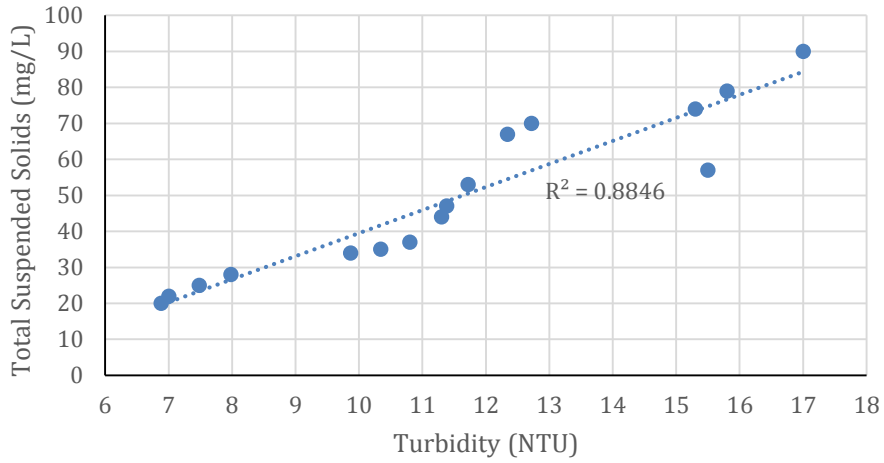

Figure 11 Correlation between Total Suspended Solids and Turbidity

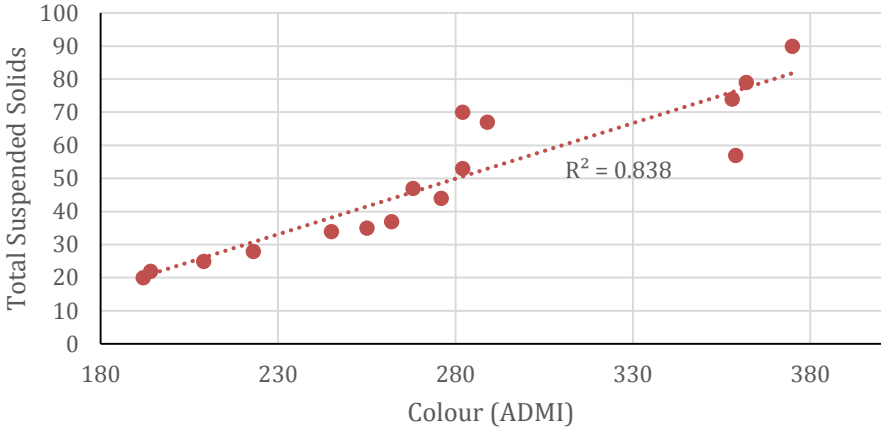

Figure 12 Correlation between Total Suspended Solids and Colour

3.4 Correlation of Total Suspended Solids, Turbidity and Colour

The relationships of total suspended solids, turbidity and colour were studied in Figures 11, 12 and 13. In Figures 11 and 12, the correlation of TSS with turbidity and colour were determined using the coefficient of determination (R^2). It was found that the R^2 value for TSS and turbidity was 0.8846, whereas for TSS and colour was 0.8380, suggesting that a strong relationship between total suspended solids with both turbidity and colour. The turbidity and colour in the POME were due to the existence of solids and organic matter in the solution [2]. Therefore, removing solids in POME will give a reduction turbidity and colour in POME. However, the turbidity and colour in the POME may be contributed by other factors as the R^2 value did not approach to 1. Thus, the correlation of turbidity with colour was further identified to learn the contributing factor for both parameters.

The correlation of turbidity with colour is depicted in Figure 13. It was found that the R^2 value for both parameters was 0.9858, indicating that the turbidity and colour possessed an extremely strong relationship. The contributing factor for both parameters were assumed to be the same other than total suspended solids in POME.

Thus, the contributing factor should be identified and removed in order to achieve a greater reduction of colour and turbidity in the POME.

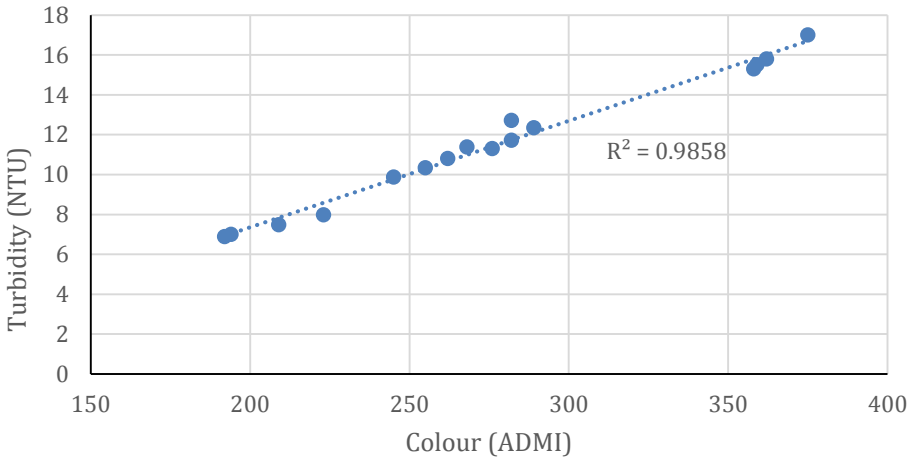

Figure 13 Correlation between Turbidity and Colour

4.0 CONCLUSION

The operating conditions for coagulation using polyaluminium chloride were optimized at pH 4, 600 mg/L of coagulant and 200 rpm of rapid mixing speed. The concentration of TiO_2 in the UF membranes only promoted the permeate flux of membranes while there were no effects on the reduction of total suspended solids, turbidity and colour due to the low concentration of TiO_2 added. The optimum transmembrane pressure (TMP) for membranes were found to be 3 bar at which the greatest percent reduction of total suspended solids, turbidity and colour was achieved. Further increasing TMP resulted in lower reduction percent reduction. The turbidity and colour existed in POME was found to be correlated to total suspended solids due to high R^2 value. However, turbidity and colour in POME might be contributed by other factors as reduction of turbidity and colour do not achieve high reduction efficiencies when total suspended solids were removed from POME.

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