

## Reuse potential of spent RO membrane for NF and UF process

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(Received December 23, 2019, Revised June 29, 2020, Accepted June 30, 2020)

**Abstract.** With the increasing demand on reverse osmosis (RO) membranes for water purification worldwide, the number of disposed membrane elements is expected to increase accordingly. Thus, recycling and reuse of end-of-life RO membranes should be a global environmental action. In this work, we aim to reuse the spent RO membrane for nanofiltration (NF) and ultrafiltration (UF) process by subjecting the spent membrane to solvent and oxidizing solution treatment, respectively. Our results showed that solvent-treated RO membrane could perform as good as commercial NF membrane by achieving similar separation efficiencies, but with reduced water permeability due to membrane surface fouling. By degrading the polyamide layer of RO membrane, the transformed membrane could achieve high water permeability (85.6 L/m<sup>2</sup>.h.bar) and excellent rejection against macromolecules (at least 87.4%), suggesting its reuse potential as UF membrane. More importantly, our findings showed that in-situ transformation on the spent RO membrane using solvent and oxidizing solution could be safely conducted as the properties of the entire spiral wound element did not show significant changes upon prolonged exposure of these two solutions. Our findings are important to open up new possibilities for the discarded RO membranes for reuse in NF and UF process, prolonging the lifespan of spent membranes and promoting the sustainability of the membrane process.

**Keywords:** end-of-life membrane; RO; UF; oxidizing agent; membrane transformation

### 1. Introduction

The significant growth of reverse osmosis (RO) membrane market over the past 10 years is mainly driven by the increasing global demand for economical and efficient water treatment solutions (Goh *et al.* 2018, Khulbe *et al.* 2012, Lee, Arnot, and Mattia, 2011). A market report indicates that the global cumulative investments in the desalination plants (mainly using RO membrane technology) is forecasted to reach \$48.2 billion by 2020 from roughly \$21.4 billion in 2015 with a compound annual growth rate (CAGR) of 17.6% (Runte 2016).

Compared to other regions, Asia-Pacific is estimated to be the fastest-growing market for the RO membrane and its process. The growth in the region can be attributed to the increasing population growth and rapid industrialization that demand greater amount of fresh water. It is undeniable that the modern RO membranes could exhibit longer lifespan than those of the membranes developed 20-30 years ago, but still the membranes are susceptible to irreversible fouling which leads to performance deterioration and requires replacement (Lau *et al.* 2014).

With the increasing demand on the RO membranes worldwide, one can anticipate the number of disposed membranes to increase accordingly. Thus, the recycling and reuse of end-of-life membranes should be a global environmental action. Currently, the end-of-life RO membranes in the industries are handled according to the waste management laws of each country, but, unfortunately, most of these discarded membranes are ended up in landfills (Lawler *et al.* 2013). The discarded RO membranes are usually left drying at atmospheric conditions, to reduce their total weight for lower shipping and disposal costs (Drioli, Giorna, and Fontananova, 2017). Disposal of membranes in landfills is still associated with many other problems and can be viewed as wasteful, environmentally damaging and costly (waste management). Furthermore, the relatively big size of commonly used 8-inch spiral wound membrane element (Diameter: 200 mm; Length: 1000 mm and weight: 16–18 kg) coupled with its compact design could take many years to achieve complete degradation in landfills. Solid wastes incineration meanwhile emits air pollutants that are of primary concern from a health effect standpoint and always receive strong objection from the public.

Transforming RO membranes into other classes of membrane process such as nanofiltration (NF) and ultrafiltration (UF) can open new possibilities for discarded RO membranes rather than landfill disposal or incineration,

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prolonging the plastic material lifetime and promoting the sustainability of the membrane process (Pontié *et al.* 2017). According to a relevant study (Landaburu-Aguirre *et al.* 2016), it is estimated that there are more than 840,000 end-of-life membrane elements (> 14,000 tons) discarded every year from the water treatment plants worldwide by considering 15% membrane replacement rate.

Over the years, there are a number of research works reporting the performance of discarded commercial RO membrane by converting it into NF or UF membrane that requires lower or non-selectivity against monovalent ions (García-Pacheco *et al.* 2015, Lawler *et al.* 2012, Pontié *et al.* 2017). These works however only characterized the properties of used RO membranes in small pieces by sacrificing the entire membrane element and taking out only small area of membrane samples. These studies did show the potential of reusing end-of-life RO membranes, but they could not represent the real industrial applications. In 2018, García-Pacheco *et al.* (2018) conducted a pilot-scale study to investigate the performance stability of recycled RO membrane for filtering raw brackish water and the results showed that the recycled membrane did not experience performance decline after 4-month filtration period. The findings of these studies strongly indicate the niche application areas of reusing recycled membranes.

In this study, we aim to conduct a more detailed investigation on both the reuse potential of discarded RO membranes for NF and UF applications as well as the resistance of the entire membrane element against chemicals that are used to transform the RO membrane into other membrane property. The spiral wound membrane element is consisted of many other materials, e.g., feed spacer, perforated tube, fiber reinforced plastic (FRP), O-rings, etc., in addition to the thin film composite (TFC) membrane and thus chemicals used to transform RO membrane should have negligible effects on these components. Industrially, the approach to transform the end-of-life RO membrane should be carried out without taking out the membrane sheet from the element and all the transformation processes must be performed *in-situ* within pressure vessel to make it practical and feasible.

## 2. Methodology

### 2.1 Membrane and chemical reagents

The spent TFC membrane used in this study was the Toray's spent TM720D-400 high rejection brackish water reverse osmosis (BWRO) membrane (hereafter referred as the spent membrane). The spent membranes were retrieved by dismantling the spent membrane module (in dry condition) provided by a local water treatment company. Isopropanol (IPA) from Merck was used to re-wet the membranes prior to any filtration experiments. Sodium chloride (NaCl, Merck), sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>, Riedel-de Haen) and magnesium sulphate (MgSO<sub>4</sub>, Merck) were used as the test solutes in assessing the separation performance of the spent membranes. The potential of directly reusing the spent membranes for NF applications was examined by

subjecting the spent membranes for the treatment of aerobically treated palm oil mill effluent (AT-POME) collected from PPNJ Palm Oil Mill Kahang, Johor, Malaysia. Potassium permanganate (KMnO<sub>4</sub>, Sigma Aldrich) was used as the oxidizing agents to degrade polyamide selective layer of spent RO membrane, converting the membrane into UF membrane with different properties. Rhodamine B (Sigma Aldrich) was used to prepare dye solution (500 ppm) and to examine the degree of polyamide layer degradation. Humic acid (HA, Acros Organics) and bovine serum albumin (BSA, Sigma Aldrich) were used as the feed solutes to study the separation performance of the converted membranes. All feed solutions for the filtration experiments were prepared using in-house prepared Milli-Q® RO water. Meanwhile, all chemicals used are of analytical grade and were used as received without further purifications.

### 2.2 Membrane preparation and conversion

For the direct usage of the spent membranes for RO and NF applications, the membranes (with circular area of approximately 18 cm<sup>2</sup> each) retrieved from membrane module were first soaked in 20 v/v% IPA for 20 min. This step is essential to recover the membrane performance (particularly membrane water flux) as the spent membrane module was kept in dry condition for some time before delivering to the laboratory. The IPA-soaked membranes were then rinsed under running tap water for several minutes before soaking in RO water until further use.

For membrane conversion, the IPA-treated spent RO membranes were soaked in 5,000 ppm KMnO<sub>4</sub> solution under active stirring. The membrane soaking time (up to 180 h) was varied to investigate the optimal time required to remove polyamide layer from the membrane top surface. The exposure intensities of membrane towards oxidizing solution were in the range of 5,000–900,000 ppm.h.

The membranes treated by oxidizing solution after every pre-determined soaking time were rinsed thoroughly under running tap water for several minutes. Subsequently, the treated membranes (with UF properties) were soaked and stored in RO water. The treated membranes were further soaked in IPA solution for 20 min prior to any filtration experiment.

### 2.3 Filtration experiment

The separation performance of the spent membranes against single salt solution (2000 mg/L NaCl, Na<sub>2</sub>SO<sub>4</sub> or MgSO<sub>4</sub> aqueous solution) and AT-POME was evaluated using a lab-scale dead-end permeation cell (HP 4750) acquired from Sterlitech Corporation, USA. The AT-POME was pre-filtered using a 0.45- $\mu$ m filter prior to use. Prior to any measurement, all membranes were compacted at a pressure of 16 bar until a stable reading on the water flux was attained. Subsequently, the membrane permeate flux and solute rejection were evaluated at 15 bar.

To confirm the successful conversion of spent membranes from RO to UF range, the converted membranes were subject to filtration of 2000 mg/L NaCl

aqueous solution. The same converted membranes were also evaluated for rejection against 100 or 500 mg/L HA and BSA aqueous solution. Unlike the spent membranes, the filtration experiment for the converted membranes were operated at compaction and operating pressure of 2 bar and 1 bar, respectively. The treated solution was started to collect for measurement only after a 10-mL permeate was produced.

The water permeability,  $J$  (L/m<sup>2</sup>·h·bar) of spent and converted membranes was calculated using the following equation.

$$J = V / (A_m \cdot \Delta t \cdot \Delta P) \quad (1)$$

where  $V$ ,  $A_m$ ,  $\Delta t$  and  $\Delta P$  represent permeate volume (L), membrane effective area (0.00146 m<sup>2</sup>), time for permeate collection (h) and operating pressure (bar), respectively. In this study, it was assumed that the osmotic pressure of the feed solutions has little and/or negligible effects on the membrane water flux owing to the low concentration of salt solution used. Thus, the  $\Delta P$  in Eq. 1 was substituted with the applied hydraulic pressure (15 bar for spent membrane and 1 bar for converted membrane) when calculating the membrane water permeability. Meanwhile, solute rejection,  $R$  (%) of the membranes was calculated using the following equation.

$$R = \left(1 - \frac{c_p}{c_f}\right) \times 100 \quad (2)$$

where  $c_f$  and  $c_p$  represent solute concentration in the feed and permeate, respectively. For filtration against NaCl, MgSO<sub>4</sub> or Na<sub>2</sub>SO<sub>4</sub>,  $c_f$  and  $c_p$  refer to the electrical conductance of the feed and permeate solution, respectively which were measured using a bench scale conductivity meter (4520, Jenway). For membrane filtration against AT-POME, the concentration of AT-POME of the feed and permeate was measured with respect to its color intensity and chemical oxygen demand (COD) using DR5000 UV-vis spectrophotometer. Meanwhile, the concentration of HA and BSA in the feed and permeate was also determined using UV-vis spectrophotometer with absorbance measured at 254 nm and 280 nm, respectively, where the maximum absorption occurs. An average of three readings were attained to yield the results of water permeability and solute rejection.

## 2.4 Characterization

The surface chemistry of spent and converted membranes were characterized using Fourier-transform Infrared (FTIR) spectrometer (Nicolet iS10, ThermoFisher Scientific) in the wavenumber of 4000–650 cm<sup>-1</sup>. The surface hydrophilicity of the spent and converted membranes was determined using a contact angle goniometer (OCA15pro, DataPhysics Instruments) via the sessile drop method using pure water as the solution. An average of 10 measurements were randomly taken from each sample to yield the results. The degree of polyamide degradation was investigated by spraying 500 ppm of Rhodamine B aqueous solution onto the membrane surface

and left for 1 min before rinsing off the red dye using RO water to reveal the stained region (Wang *et al.* 2012). The staining area of each membrane was fixed at 1 cm × 1 cm.

To assess the resistance of other main components (e.g., feed spacer, permeate channel, perforated tube and O-ring) found in the membrane module against the oxidizing solution (KMnO<sub>4</sub>) and IPA solvent, these components were soaked separately in the respective solution for up to 24 days and the changes in chemistry properties and weight were investigated using FTIR spectrometer (Nicolet iS10, ThermoFisher Scientific) in the wavenumber of 4000–400 cm<sup>-1</sup> and precision digital balance with readability up to 0.001 g.

## 3. Results and discussion

### 3.1 Filtration Performance of Spent BWRO Membranes

It is necessary to understand the separation performance of the spent RO membrane prior to evaluating its potential for direct usage in NF application. In this study, the spent membranes were subjected to rejection against monovalent (i.e., NaCl) and divalent salts (i.e., Na<sub>2</sub>SO<sub>4</sub> and MgSO<sub>4</sub>). From the filtration results given in Fig. 1, it was found that the pure water permeability (PWP), NaCl, Na<sub>2</sub>SO<sub>4</sub> and MgSO<sub>4</sub> rejection of the spent membrane was recorded at 2.03 L/m<sup>2</sup>·h·bar, 86.22%, 90.76% and 88.71%, respectively. It is worth noting that the virgin RO membrane (TM720D-400) exhibits PWP and NaCl rejection of 3.02 L/m<sup>2</sup>·h·bar and 99.8%, respectively. This means that both water permeability and salt rejection were significantly reduced by 32.8% and 13.6%, respectively when the membrane was discarded. The lower water permeability of the spent membrane could be attributed to increased hydraulic resistance resulting from membrane surface fouling. Meanwhile, the inferior salt rejection of the spent membranes could be due to reduced water permeability and/or deterioration of the membrane selective layer.

As the membranes in the spiral wound element might experience different degree of surface fouling, some of the membrane areas taken for testing might suffer from larger deviation. For instance, water permeability of the membrane used during MgSO<sub>4</sub> solution filtration showed larger standard deviation compared to the filtration of NaCl and Na<sub>2</sub>SO<sub>4</sub> solutions.

In our previous work (Abdullah *et al.* 2018), it was demonstrated that commercial NF90 and NF270 membranes (from Dow FILMTEC) could exhibit MgSO<sub>4</sub> rejection of 98.5 and 83.7%, respectively. By comparing the MgSO<sub>4</sub> rejection of the spent membrane (obtained in this study) with the two NF membranes, it may be reasonable to presume that the spent membrane exhibits separation performance between tight NF (NF90) and loose NF (NF270) range, although the spent membrane exhibits much lower water permeability (2.03 L/m<sup>2</sup>·h·bar) than both types of the NF membranes (~4.42 and ~11.16 L/m<sup>2</sup>·h·bar for NF90 and NF270, respectively). These findings suggest that the spent RO membrane might be suitable for direct usage for NF application, provided that high water permeability is

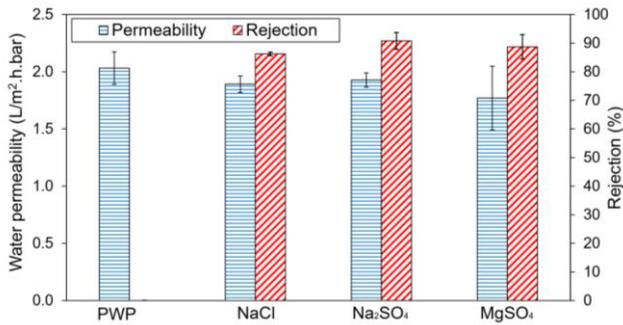


Fig. 1 Performance of spent BWRO membrane for filtration of pure water and aqueous salt solutions

Table 1 Direct usage of spent BWRO membrane for NF process of AT-POME

Parameter	Feed	Permeate	Removal (%)
Conductivity ( $\mu\text{S/cm}$ )	7573.33	453.67	94.01
Color (ADMI)	1944.44	24.11	98.76
COD (mg/L)	396.67	5.11	98.71
pH	8.89	7.84	-

not required. The potential of directly reusing the spent membrane for NF application will be further assessed in section 3.2.

### 3.2 Direct Usage of Spent RO Membrane for NF Application

In this section, the spent membrane was subjected to filtration of specific industrial effluent discharged from local industry, i.e., AT-POME to evaluate its potential for direct usage in NF application. Unlike POME, AT-POME contains much lower organic pollutants as it has been aerobically-treated on site to reduce the levels of COD and BOD. The use of NF membranes for AT-POME treatment has been reported in the literature in which promising color removal rates (up to 98.92%) were able to achieve using commercial NF membranes (NF90 and NF270) (Abdullah *et al.* 2018, Simon and Nghiem, 2014, Tan *et al.* 2018).

Table 1 shows the performance of spent RO membrane for the treatment of AT-POME with respect to several important parameters. As can be seen, the spent RO membrane was able to significantly reduce the values of conductivity, color and COD, recording removal rate of 94.01%, 98.76% and 98.71%, respectively. Its color removal rate was in good agreement with the NF90 membrane used for the same treatment as reported in the work of Abdullah *et al.* (2018). With respect to conductivity removal rate, it was found that spent RO membrane demonstrated much higher rejection value (94.01%) compared to the same membrane (78.66%), owing to its denser polyamide selective membranes. It must be noted that the spent RO membrane suffered from lower water permeability (1.91 L/m<sup>2</sup>.h.bar) in comparison to the NF90 membrane (>2.0 L/m<sup>2</sup>.h.bar) as a result of surface fouling.

On the other hand, it was noticed that the pH of the treated sample was close to the neutral condition, indicating

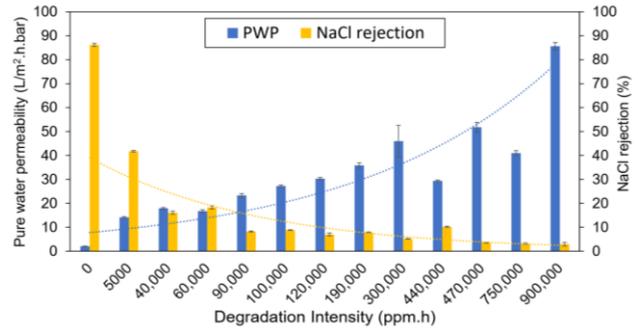


Fig. 2 Effect of degradation intensity on the spent BWRO membrane performance with respect to pure water permeability and NaCl rejection

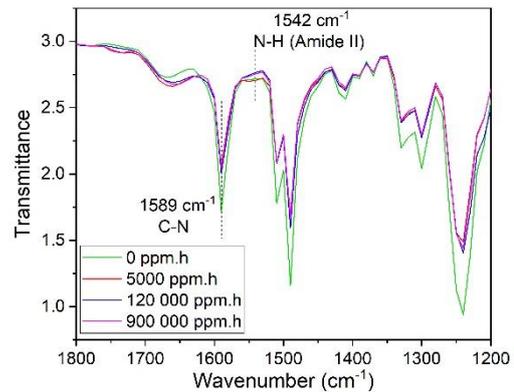


Fig. 3 FTIR spectra of KMnO<sub>4</sub>-treated spent membrane

the spent RO membrane could remove undesirable ions. Such result was correlated to the lower conductivity value of the treated sample.

### 3.3 Transformation of Spent RO Membranes into UF Membranes

#### 3.3.1 Effect of oxidizing agent and its intensity on membrane performance

In order to transform the spent RO membrane into UF membrane, oxidizing agent - KMnO<sub>4</sub> was used. KMnO<sub>4</sub> was commonly reported in the literature to degrade/remove polyamide selective layer of TFC membrane (Ambrosi and Tessaro, 2013, Rodríguez *et al.* 2002). Fig. 2 shows the effect of degradation intensity of KMnO<sub>4</sub> on the pure water permeability and NaCl rejection of spent RO membrane. Obviously, this oxidizing agent was able to degrade polyamide selective layer by improving membrane pure water permeability. The membrane pure water permeability was increased from ~2 to as high as 85.6 L/m<sup>2</sup>.h.bar with increasing degradation intensity from zero to 900,000 ppm.h. This indicated that the greater the degradation intensity the higher the water permeability produced.

The trend of the membrane water permeability is inversely proportional to the trend of salt rejection in which the NaCl rejection decreased from 86.2% to < 5%.

Fig. 3 shows the FTIR spectra of the KMnO<sub>4</sub>-treated spent membranes treated at different degradation intensity. All spectra are normalized to band at 1245 cm<sup>-1</sup>,

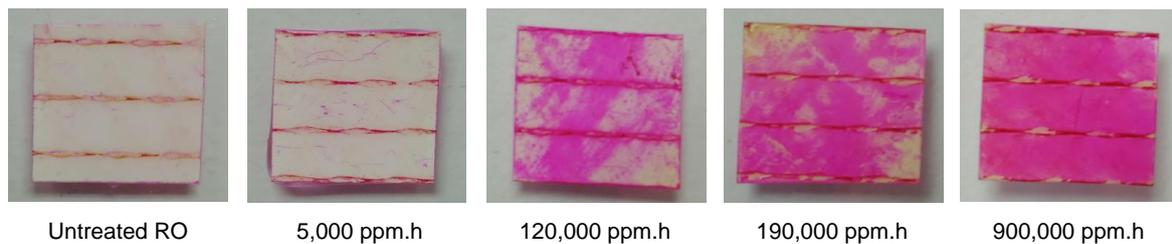


Fig. 4 Photos of spent BWRO membrane treated by  $\text{KMnO}_4$  at different degradation intensity that were stained with Rhodamine B

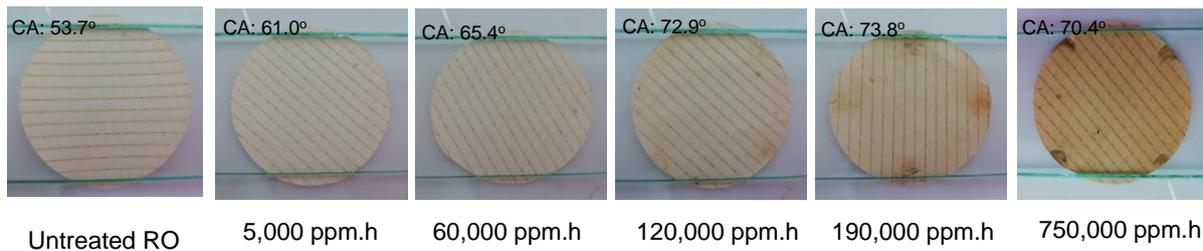


Fig. 5 Photos of spent BWRO membrane treated by  $\text{KMnO}_4$  at different degradation intensity and their respective surface water contact angle

representing the phenylene ether stretching vibration of polysulfone (PSf) that remained unchanged throughout the entire oxidation process. Obviously, we can see that the peak intensity of the membranes at  $1589\text{ cm}^{-1}$  and  $1542\text{ cm}^{-1}$  that corresponded to C-N stretching and N-H bending (amide II), respectively, were reduced upon  $\text{KMnO}_4$  treatment. This is a strong indication of the degradation of polyamide layer. In addition, it is found that the peak intensity of  $\text{KMnO}_4$ -treated membranes at  $1485\text{ cm}^{-1}$  that is belonged to the C=C aromatic ring stretching was significantly lower than that of un-treated RO membrane. Detection of weak signal at  $1660\text{ cm}^{-1}$  for all membranes could be attributed to the presence of C=O stretching (amide I). It must be pointed out that the characteristic peaks belonging to the polyamide layer could still be found in the  $\text{KMnO}_4$ -treated spent membrane and this could be possibly due to the polyamide that was trapped within the pore structure of the microporous substrate. The typical depth of the reflected IR beam penetration in the ATR technique is around  $1\text{ }\mu\text{m}$  (much larger than the thickness of polyamide layer, i.e., several hundreds of nm), thus it is highly possible that the polyamide that is trapped in the substrate pores could be detected particularly in the case where polyamide layer became thinner upon degradation. Our results are in good agreement with the work conducted by García-Pacheco et al. (2015) in which the peak signals of aromatic amide bonds (of polyamide layer) were still detected (but at lower intensity) on the transformed membrane.

To further examine the extent of polyamide layer degradation, Rhodamine B test was carried out on the surface of  $\text{KMnO}_4$ -treated spent membrane and the results are presented in Fig. 4. As the degradation intensity increased, staining region of the membranes was found to increase accordingly. This is because the degradation of

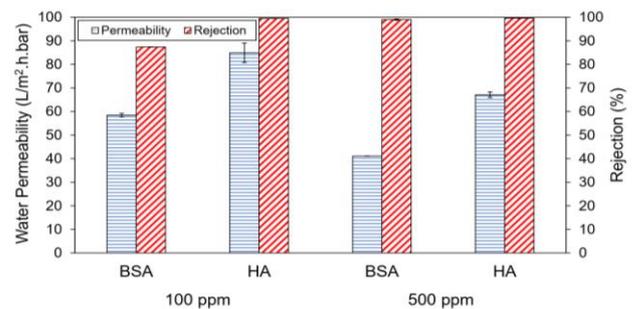


Fig. 6 Separation performance of  $\text{KMnO}_4$ -treated spent membranes (900,000 ppm.h) for UF of HA and BSA solution

polyamide layer allows Rhodamine B to stain strongly on polysulfone substrate surface. These findings revealed that polyamide layer was almost completely disappeared upon exposure to degradation intensity of 900,000 ppm.h.

Fig. 5 presents the samples of membranes treated by  $\text{KMnO}_4$  solution at different degradation intensity. The presence of straight lines on the spent membrane surface was the result of the non-woven feed spacer that was placed on top of the polyamide layer in the spiral wound element. It can be evidenced from the images that the membrane surface changed from light brown to darker color with increasing degradation intensity. The darker surface revealed that  $\text{KMnO}_4$  was likely to oxidize the substrate membrane, causing it to age at prolonged degradation. The increase in water contact angle from  $\sim 53.7^\circ$  in the untreated membrane to  $>70^\circ$  in the  $\text{KMnO}_4$ -treated membrane could suggest the removal/reduction of polyamide layer as the high water contact angles (in the range of  $60\text{--}74^\circ$ ) obtained were close to the range of water contact angle of typical polysulfone substrates (i.e.,  $66\text{--}71^\circ$ ) reported

Table 2 Weight change of different parts of spiral wound element upon exposure of KMnO<sub>4</sub> solution (5,000 ppm)

<sup>a</sup> Parts	Main Material	<sup>b</sup> Weight Change (%)	
		7 Days	21 Days
Perforated tube	Acrylonitrile butadiene styrene	-	-
Fiber reinforced plastic (FRP) body	Fibre glass with polyester resin	-	-
Non-woven fabric	Polyester	-	8.33
Permeate spacer	Polyester	-	-
End cap	Acrylonitrile butadiene styrene	-	-
O-ring	Ethylene propylene diene monomer	-	-
Feed spacer	Polypropylene	-	9.09

<sup>a</sup> Initial weight of items was in the range of 0.1–3.0 g.

<sup>b</sup> Degradation intensities for 7 and 21 days are equivalent to 840,000 and 2,520,000 ppm.h, respectively.

elsewhere (Misdan *et al.* 2013). In comparison to the contact angle of pristine RO membrane (brackish water type, 58.01°) (Ng *et al.* 2019), the change in the contact angle of the spent RO membrane is mainly due to the deposition/adsorption of foulants onto the membrane surface.

### 3.3.2 Performance of transformed UF membrane

In this section, the performances of KMnO<sub>4</sub>-treated spent membranes for UF filtration process were assessed for macromolecules removal and the results are presented in Fig. 6. At 100 ppm feed solution, the transformed membranes were reported to be able to achieve excellent removal rates for both BSA (87.4%) and HA (99.5%) with water permeability recorded at 58.4 and 84.9 L/m<sup>2</sup>.h.bar, respectively. Water permeability of BSA solution filtration was significantly lower than the water permeability of HA solution because BSA is a bio foulant that has strong affinity towards the polymeric substrate, causing severe fouling problem as a result of adsorption/deposition. The water permeabilities of the membranes were further reduced when they were used to treat the same solution but at higher solute concentration, i.e., 500 ppm. It is due to the significant concentration polarization effect and/or severe fouling issue. Even though the water permeabilities were negatively affected at higher concentration, the efficiency of transformed membranes for BSA and HA removal was not affected. The findings suggested that it is highly possible for the transformed membrane to be reused for UF process.

### 3.4 Effect of oxidizing agent on other parts of spiral wound element

There is very little information about the impact of oxidizing agent (or its degradation intensity) on the stability of other parts of spiral wound element (besides the TFC membrane itself) in the open literature. If the membrane transformation is to be performed *in-situ* (by circulating the oxidizing solution through the spiral wound element), one must also ensure other materials in the element do not degrade as the polyamide layer.

Table 2 compares the weight changes of the different parts of spiral wound element that were measured after 7

- and 21-day of exposure to 5000 ppm KMnO<sub>4</sub> solution. The weight of all the components (except non-woven fabric and feed spacer) remained unchanged after 21 days of KMnO<sub>4</sub> solution exposure, indicating that oxidizing agent was only attacking the polyamide materials and have minimal impacts on other parts of element.

Figure 7 further compares the FTIR spectra of these components exposed to different days of KMnO<sub>4</sub> solution. As clearly shown, there was insignificant difference between the characteristic peaks of each component irrespective of exposure days of KMnO<sub>4</sub> solution. The significant peak absorbances of the main material used for each component manufacture could clearly be detected, suggesting KMnO<sub>4</sub> solution did not oxidize them. Figure 8 meanwhile presents the organic structure of each material used for membrane element fabrication. Considering the spent RO membrane requires more or less 900,000 ppm.h degradation intensity to achieve desired flux and rejection, the prolonged exposure of components to 21 days of oxidizing solution (equivalent to 2,520,000 ppm.h) is beyond the degradation intensity required by the transformation process and thus would not deteriorate spiral wound element.

The impact of solvent on the stability of components of spiral wound element was also assessed and the results are presented in Table 3. As mentioned in the methodology section, pure IPA solvent was used prior to oxidizing solution in an attempt to recover the membrane performance (particularly membrane water permeability) as the spent RO membrane module was kept in dry condition for some time before delivering to the laboratory. The results indicated that IPA has stronger impact compared to the oxidizing solution in reducing the weight of components. Almost all the components (except perforated tube) experienced weight loss after 21-day of IPA exposure. End-cap and O-ring in particular experienced early weight loss after 7 days of IPA exposure. Nevertheless, considering the transformation is only performed once and the contact time between spent membrane and IPA is rather short (20 min in our study), we can say that short IPA exposure period would not affect the stability of the entire spiral wound element.

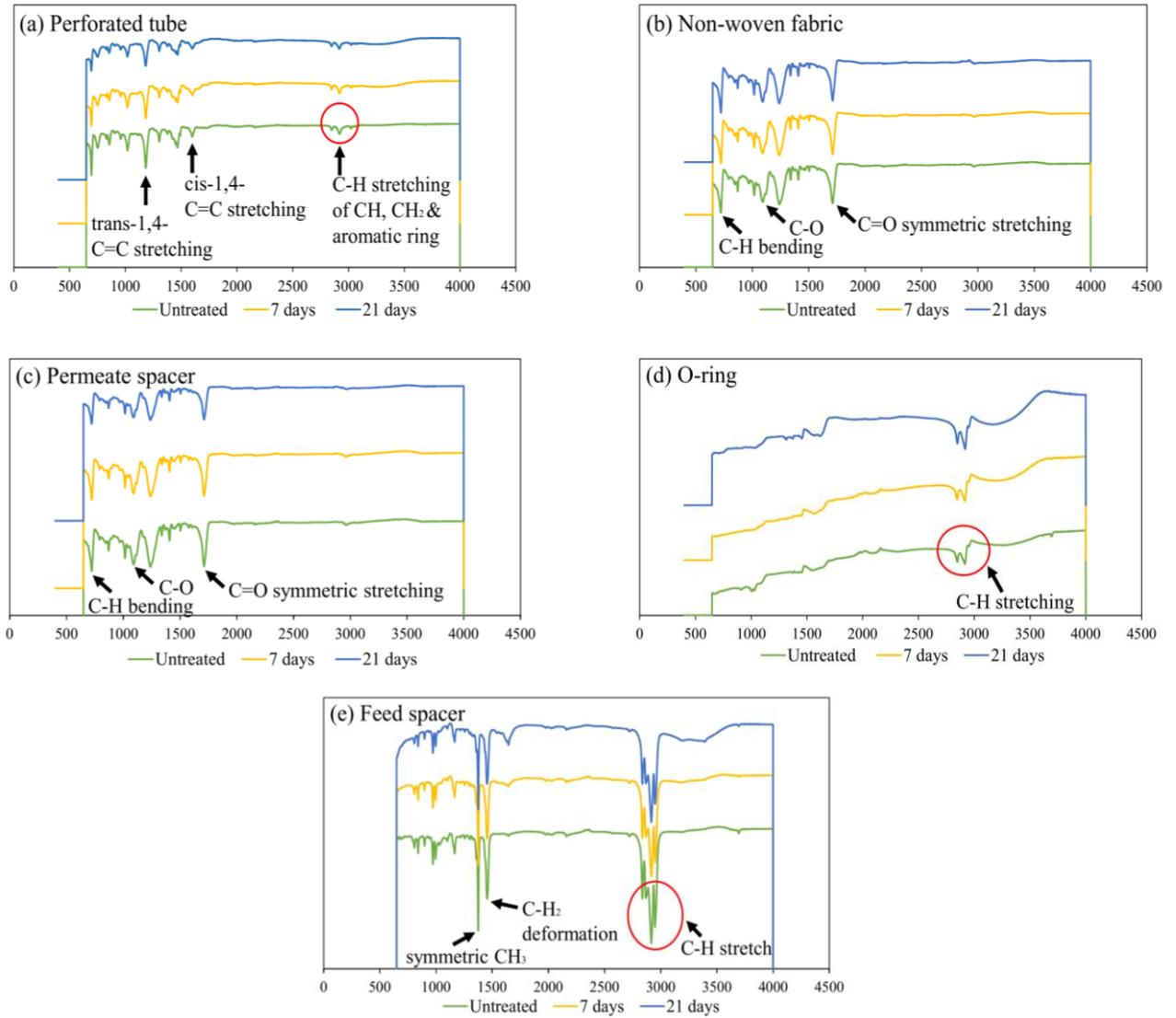


Fig. 7 FTIR spectra of different parts of spiral wound element after exposure of  $\text{KMnO}_4$  solution for 7 and 21 days. (Note: The FTIR spectra of FRP body and end-cap are not measured as FTIR analysis could not be performed on non-flat sample)

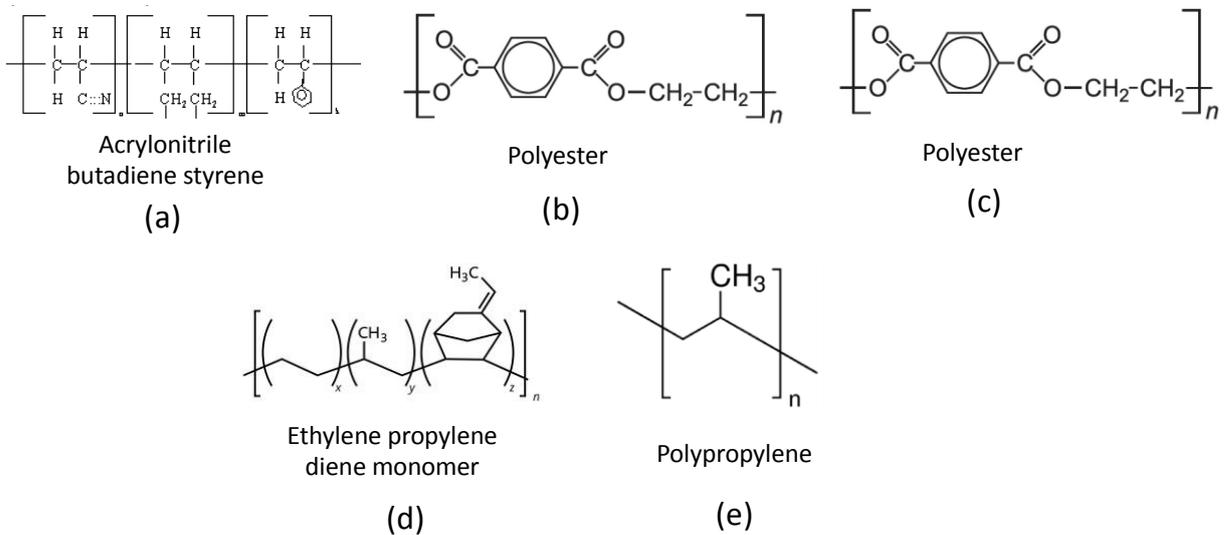


Fig. 8 Organic structure of materials used for membrane element fabrication, (a) perforated tube, (b) non-woven fabric, (c) permeate spacer, (d) O-ring and (e) feed spacer

Table 3 Weight change of different parts of spiral wound element upon exposure of pure IPA solvent

Parts	Weight Change (%)	
	7 Days	21 Days
Perforated tube	-	-
FRP body	-	0.35
Non-woven fabric	-	9.09
Permeate spacer	-	11.11
End cap	0.68	2.80
O-ring	0.92	0.94
Feed spacer	-	15.38

<sup>a</sup>Initial weight of items was in the range of 0.11–3.27 g.

#### 4. Conclusions

In this work, we have demonstrated the potential of direct reuse of spent RO membrane for NF process for AT-POME treatment after post-treating the spent membrane with IPA solvent. Results revealed that the IPA-treated RO membrane could perform as good as commercial NF membrane by achieving similar rejection rates for several parameters, but with lower water permeability due to the surface fouling. Further investigation indicated that the spent RO membrane could be fully transformed into UF membrane by exposing the spent membrane to oxidizing solution. The pure water permeability of spent RO membrane was significantly increased from ~2 to as high as 85.6 L/m<sup>2</sup>.h.bar with increasing degradation intensity of KMnO<sub>4</sub> solution from zero to 900,000 ppm.h. Upon transformation, the resultant membrane exhibited < 5% NaCl rejection. It must be pointed out that the transformed RO membrane could attain high BSA and HA rejections (87.4–99.5%) with reasonably high water permeability, suggesting its reuse potential as UF membrane. More importantly, our studies showed that *in-situ* transformation on the spent membrane using IPA and oxidizing solution could be safely carried out as the materials of the entire spiral wound element did not show significant change in terms of weight and characteristic peaks upon prolonged exposure of these two solutions. Our findings are important to open up new possibilities for the discarded RO membranes for reuse in NF and UF process, prolonging the lifespan of spent membranes and promoting the sustainability of the membrane process.

#### Acknowledgments

The authors would like to thank Universiti Teknologi Malaysia (UTM) for providing UTMSHINE Signature Research Grant (Vot no. Q.J130000.2451.07G79) to financially support the research work conducted.

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