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Performance of reverse osmosis (RO) for water recovery from permeates of membrane bio-reactor (MBR)

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ABSTRACT

In this study, permeate from a hollow fiber polyethylene (PE) membrane bio-reactor (MBR) system treating synthetic agricultural wastewater was fed into a cellulose acetate brackish water reverse osmosis (BWRO30 2540) membrane system; three different trans-membranes pressures (TMPs) of 1000, 2500, and 4000 kPa were selected to evaluate the system performance in terms of general operating parameters as well as the removal of chosen important potential fouling water quality parameters. The results showed that highest corrected permeate flux rate was at a TMP of 2500 kPa, whereas lowest recorded at a TMP of 4000 kPa. Similar situation prevailed in water recovery rate. But temperature corrected specific fluxes decreased as the applied TMPs increased. In all selected TMPs, more than 96% of salinity was removed. Permeate from MBR as feed to reverse osmosis required frequent chemical cleaning than the microfiltration/ultrafiltration (MF/UF) permeates and granular media filter (GMF) filtered in order to maintain the required rate of product water. One of the reasons for this frequent chemical cleaning is due to higher total organic carbon as well as total nitrogen (TN) in the MBR permeate. This result needs to be further evaluated through field trials.

Keywords: Agricultural wastewater; Brackish water reverse osmosis; Membrane bio-reactor; Water recovery

1. Introduction

Reverse osmosis (RO) membrane processes are among the most important, widely commercialized and versatile water treatment technologies for twenty-first century [1]. It is also a viable technology for water reclamation [2]. However, the performance of this membrane during water recovery from wastewater is often limited by membrane fouling. Wastewater contains three potential membrane fouling categories, microbial (bacteria, viruses, etc.), organic (natural organic matter), and inorganic (minerals) contents [3]. For this reason, RO membrane fouling is prevalent in water reclamation applications [4].

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Among the effective fouling control strategies, application of the suitable pre-treatment options may be the best one to prevent the membrane fouling as applied options tries to minimize materials responsible for this phenomenon. Pre-treatment is emerging as a most promising solution to control the foulants as it is simple and easy to implement [5]. One of the strategies for minimizing RO membrane fouling is integrated membrane systems, as this integration has shown successful and encouraging performance in reducing the potential fouling water quality parameters (PFWQPs) and achieving steady permeate flux with less cleanings [5,6].

In the wastewater recovery, controlling the membrane fouling is challenging because of presence of suspended solids (SS) and colloidal matter with high level of biological activity. A study concluded that particles smaller than 0.45 μm, including colloids and dissolved solids, contributed more to fouling than particles larger than 0.45 μm [7]. In addition, others foulants such as low molecular weight dissolved organic components, sparingly soluble salts, metal oxides and hydroxides and biological agents are also responsible for causing RO fouling during wastewater recovery [6]. The water and other valuable nutrients from agricultural wastewater need to be recovered and harmful pesticides residual need to be reduced and treated before discharging to nature. Membrane bio-reactors (MBRs) are proven to be effective for treating this type of agricultural wastewater and further reduce the fouling potentiality on RO membranes during water and nutrients recovery.

Combination of membrane modules submerged in the activated sludge called as MBR, which reduces footprint significantly compared with the combination of conventional treatment followed by sand filtration or ultrafiltration. The MBR pretreatment might be the suitable option for increasing water recovery as well as the reduction of PFWQPs. In the previous ranking study of the membrane pretreatments, MBR stood as the potential candidate for RO pretreatments in biologically treated wastewaters recovery [8].

In addition, submerged MBRs are the most recent membrane technology to be applied for the pre-treatment of secondary effluent prior to RO treatment [6]. MBR use membranes to provide separation of the mixed liquor solids at the end of the activated sludge process in place of the conventional gravity secondary settling tanks. In this process, a small pressure differential is used to collect high-quality effluent on the permeate side of the membranes while, the biomass remains inside the activated sludge process.

The last decade has seen a tremendous acceleration of MBR application at full-scale which has solidified MBRs as a key wastewater treatment technology [9]. MBRs are now an established and accepted technology with higher reliability for municipal wastewater treatment for higher quality effluents production [10]. The pilot-scale experimental results demonstrated that MBR can be used for dual purposes, namely as biological secondary/tertiary treatments as well as pre-treatment for RO during as MBR/RO integration gave excellent quality product water during water recovery [11].

Though MBR proven mature technology for municipal wastewater reclamation [10], so far few studies are conducted the studies about the comparison of this technology with other low membrane filtration (MF/UF) and conventional pre-treatment technologies.

The objectives of the study are to evaluate the performance of MBR/BWRO membrane systems, to compare MBR/BWRO membrane systems performance with MF/BWRO, UF/BWRO and GMF/BWRO, integrated systems. The performance evaluation and comparison are based on the quantitative values of major operating parameters as well as PFWQPs.

2. Materials and methods

2.1. Feed water

The synthetic feed was prepared in controlled laboratory conditions. Table 1 shows the composition of the synthetic feed solution used to operate the laboratory-scale MBR during the studies and its chemical oxygen demand (COD) concentration was maintained at around 700 ± 50 mg/L [12].

The effluents from the laboratory-scale MBR ([A hollow fiber polyethylene [PE] membrane module (pore size 0.4 μm, effective area 0.2 m^2]) were fed into

Table 1
Composition of synthetic feed [12]

Chemical component	Concentration (mg/L) ± 5%
Glucose ($C_6H_{12}O_6$)	710
Ammonium acetate (CH_3COONH_4)	200
$NaHCO_3$	750
NH_4Cl	30
KH_2PO_4	30
K_2HPO_4	60
$MgSO_4 \cdot 7H_2O$	50
$CaCl_2 \cdot 2H_2O$	30
NaCl	30

the BWRO. The characteristics of the influent and effluent are given in Table 2.

2.2. Pilot-scale RO membrane plant and experimental set up

A pilot scale cellulose acetate brackish water reverse osmosis (BWRO30 2540- surface area 2.6 m^2) membrane plant (Fig. 1) was used for the water recovery and PFWQPs reduction analysis.

The four different types of membranes are selected for studies. The characteristics of studied membranes are given briefly in Table 3.

In this study, permeate (influent agricultural wastewater) of a hollow fiber polyethylene (PE) MBR system was feed into the RO membrane system, and three different trans-membranes pressures (TMPs) of 1,000, 2,500, and 4,000 kPa were selected to evaluate the system performance in terms of general operating parameters as well as reduction in the chosen important PFWQPs. In the initial stage of experiment, the synthetic agricultural wastewater of known constituents was fed into MBR and later collected MBR permeate was fed into BWRO.

In addition, for the purpose of comparison, three others best ranked pre-treatments [8], namely MF (synthetic secondary effluent feed), UF (synthetic secondary effluent feed), and GMF (real secondary effluent feed) were chosen, and permeates from these pre-treatments were fed into BWRO for comparing the performance and quality against the MBR permeate as feed to RO. In all cases, PFWQPs were analyzed at three different steps; at first pre-treatment influent, then pre-treatments effluent and finally BWRO effluent. The feed, permeate, and retentate samples were taken and analyzed at the beginning and the end of operations.

The RO membrane (BWRO30 2540) system (Fig. 1) was chosen and operated for performance evaluation based on the measurements of operating parameters and PFWQPs of permeates emerging from MF, UF, MBR, and GMF pre-treatments at different trans-membrane pressures (TMPs).

2.3. Evaluation of parameters and analytical methods

The operating parameters such as flow rate, temperature, feed pressure, retentate pressures, and

Table 2
Water quality parameters of MBR influent, effluent and BWRO effluent

Parameters, feed types and values	Chemical component with values						
	COD (mg/L)	UV_{254nm}	Turbidity (NTU)	pH	TN (mg/L)	Nitrates (mg/L)	TP (mg/L)
MBR feed (influent)	700–800	0.078	DNM[a]	6.2–7.4	34	DNM	67.25
MBR effluent	16	0.153	0.18	7.83	20	13.5	58.75
BWRO effluent	7.73	0.008	0.10	7.34	6.06	DNM	0.31

[a]DNM = do not measure.

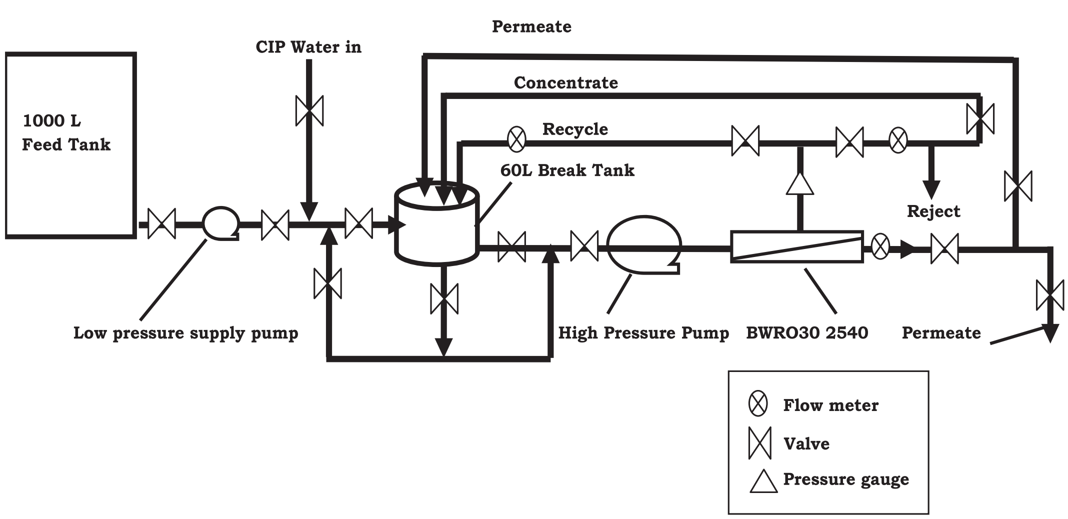

Fig. 1. Schematic diagram of BWRO system.

Table 3
Characteristics of selected membranes units

Membranes	Microfiltration (MF)[a]	Ultrafiltration (UF)[a]	Membrane bio-reactor (MBR)	Reverse osmosis (RO)[b]
Membrane specification	Tubular ceramic micro-filtration membrane (INSIDE CeRAM)	Tubular ceramic ultra-filtration membrane (INSIDE CeRAM)	A hollow fibre polyethylene (PE)	Brackish water membrane (BW30-2540)
Manufacturer	Tami industries	Tami industries	NA[a]	DOW FILMTECH™
Membrane material	Zirconium/titanium dioxide	Zirconium/titanium dioxide	polyethylene (PE)	Cellulose acetate
Membrane characteristics	Hydrophilic	Hydrophilic	Hydrophilic	Hydrophilic
Pore size	1.4 µm	1 kDa	0.4 µm	not applicable
Membrane chemistry	Zirconium/titanium dioxide	Zirconium/titanium dioxide	polyethylene (PE)	Cellulose acetate
Type	Ceramic tubular	Ceramic tubular	A hollow fibre	Thin-film composite; spiral wound
Surface area (m^2)	0.50	0.35	0.20	2.6
Operating TMP range (kPa)	50–350	50–350	NA[c]	500–4,100
Operating pH	0–14	0–14	NA	2–11
Operating temperature (°C)	<350 (but changes in temperature must be lower than 10 °C/min	<350 °C (but changes in temperature must be lower than 10 °C/min	NA	<45 °C
CIP	Present	Present	NA	Present

[a]DU, Standard Operating Procedure for Pilot Scale Membrane Filtration Unit, Deakin University 2006a, 38pp; [b]DU, Standard Operating Procedure for Pilot Scale RO Membrane Filtration Unit, Deakin University, 41pp; [c]NA not available.

permeate pressures were measured with the help of graduated gauges in built in membrane plants. During filtration experiments, the MBR permeate was fed into the RO membranes, and different operation parameters were recorded at the selected TMPs. The important equations used for operation parameters analysis were briefly described in the below paragraphs.

2.3.1. Permeate flux/corrected permeate flux

Permeate flux was calculated given in the formula below Eq. (1). Because the flux is greatly affected by water temperature, the flux was normalized to a standard temperature of 20°C in case of LPMS (25°C in case of HPMS) to account for fluctuations in water viscosity:

$$J = Q_p/A_{system} \tag{1}$$

where J is permeate flux (L/m^2 h), Q_p is permeate flow (L/h), and A_{system} is surface area of the membrane system (m^2).

2.3.2. Transmembrane pressure (TMP)

The TMP of the membrane system is an overall indication of the feed pressure requirement; it was used, with the flux, to assess membrane fouling.

For cross-flow mode of operation:

$$TMP = (P_F + P_C/2) - P_P \tag{2}$$

where TMP is trans-membrane pressure (kPa), P_F is feed pressure (kPa), P_C is concentrate/retentate pressure (kPa), and P_P is permeate pressure (kPa).

For the direct-feed mode of operation:

$$TMP = (P_F - P_P) \tag{3}$$

2.3.3. Total hydraulic membrane resistance (R_t)

The total hydraulic membrane resistances were measured by using fouling equation resistance in series model [13]. According to constant pressure theory, the permeate flux J is expressed by the resistance in-series model.

$$J = \Delta P \mu R_t \quad (4)$$

where J is permeate flux, ΔP is the TMP, μ the permeate viscosity, and R_t the total hydraulic resistance.

2.3.4. Water recovery percentage (WR%)

The water recovery percentage is the percentage of feed that is converted to permeate is called the recovery (water or liquid) of the membrane system. The WR% was calculated by the below given formula.

$$WR\% = (Q_p/Q_f) \times 100\% \quad (5)$$

where WR% is water recovery percentage, Q_p is permeate flow (L/h), and Q_f is feed flow (L/h).

The selected physical and chemical PFWQPs were measured in accordance with the standard Methods of American Public Health Association, American Water Works Association, and Water Environment Federation [14].

The TSS (dried at 103–105°C), TDS (dried at 180°C); turbidity and electrical conductivity (EC) were analyzed according to the standard methods [14]. The particles that cause light scattering, which is measured as turbidity, vary in size between 1 and 1 mm [15] was also analyzed during the studies.

The UV absorbance at 254 nm is a more suitable surrogate for DOC concentration/character than true color, and it is effective within this 254 nm wavelength [14]. For this reason, UV254 nm was selected and analyzed as systems evaluation parameter by using the Merck Spectrophotometer (Spectroquant® Pharo100).

During these studies, EC, dissolved oxygen (DO), pH and turbidity were measured using Conductivity Meter (WTW LF330), DO Meter (WTW Oxi320), pH Meter (WTW 320), and Turbidity Meter (HACH 2100P) respectively. COD, TN and TP measurements were carried out adopting photometric method using Merck Spectrophotometer (Spectroquant® Pharo100), Merck cell test kits (for COD, TN, and TP) and HACH COD-reactor 45600-00. In addition, total carbon (TC), inorganic carbon (IC), total organic carbon (TOC), and total nitrogen (TN) were measured and analyzed using the Shimadzu TOC-L or TOC-TNM Analyzer.

Each sample was analyzed in duplicate or triplicate with six different samples at various TMPs and operation times. For example, in case of pre-treatments, samples were collected in 3 different TMPs 100, 200, and 300 kPa on the basis of 1 and 4 h. The RO membrane samples were collected in the same collection time phase but with different TMPs (1,000, 2,500, and 4,000 kPa).

2.4. RO membrane system chemical cleaning

The chemical cleaning of the BWRO30 2540 was done as according to the requirements three conditions, namely significant drop in the permeate flow rate (approximately less than 10% of the designed output flow rate), significant rises in permeate conductivity (approximately 10% increase in the permeate stream), and the significant rise in TMPs. The chemical cleanings of the RO membrane system were also done, when this system stop for longer than couples of hours as well as before changing the feed samples types.

In order to chemically clean the RO membrane, experiments followed the caustic chemical rising, and soaking to remove the SSs, colloids, and organic compounds. This was performed at pH value of 11 and temperature of 40°C for optimum results. The sodium hydroxide solution (10%) was used for caustic chemical cleaning. The RO membrane was soaked with this chemical overnight before rising in order to obtain the

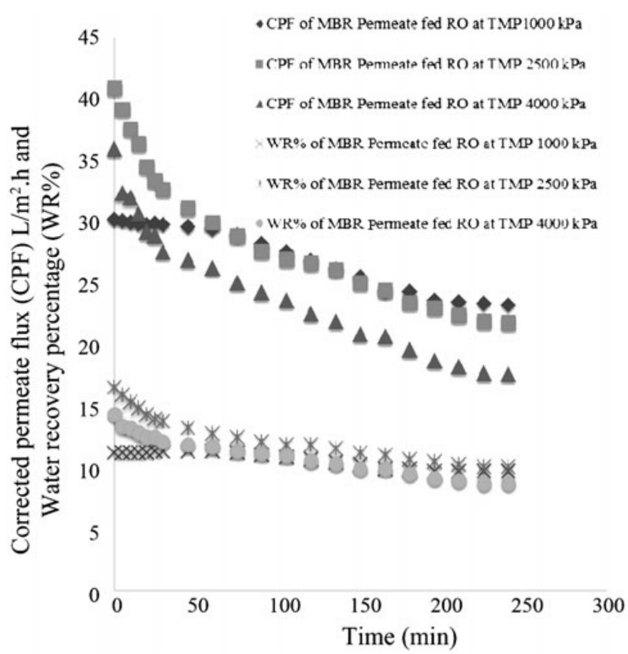

Fig. 2. Corrected permeate fluxes (L/m^2 h) and water recovery percentages (WR%) of MBR permeate fed RO membrane at different TMPs.

best chemical cleaning outputs. After that step, rinsing was conducted to remove the chemical residual and recorded the permeate flow rate after cleaning.

3. Results and discussion

3.1. Performance in terms of operational parameters

The results showed that highest corrected permeate flow rate was obtained at a TMP of 2,500 kPa; whereas lowest recorded at 4,000 kPa (Fig. 2). In addition, permeate fluxes dropped significantly in the case of 4,000 and 2,500 kPa TMPs, whereas decreased slowly in case of 1,000 kPa (Fig. 2). After approximately 80 min of filtration, the corrected permeate fluxes at TMP of 2,500 and 4,000 kPa dropped below than the fluxes at TMP of 1,000 kPa. In the membrane filtration, generally when the TMP increases the fluxes will increases but when the total membrane resistance increases the fluxes will decreases. Depending on the influence of TMP and total membrane resistance the flux will either increases or decreases. In the conducted filtration experiments with MBR permeate feed, when TMP increase from 1,000 to 2,500 kPa, the initial flux increased indicating the influence of TMP was dominating. On the other hand, when the TMP increased from 2,500 to 4,000 kPa, total resistance was dominated (Fig. 2). This may be the reason for recording the lower permeate fluxes in higher TMP of

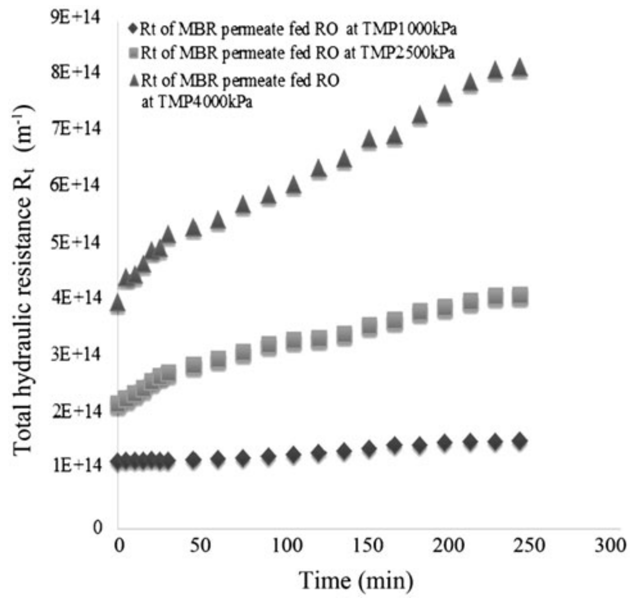

Fig. 3. Total hydraulic resistance (R_t) of BWRO (with MBR permeate feed) at various TMPs.

Table 4
Performance of RO membrane in term of operation parameters with chemical cleaning frequency at various feeds/TMPs

Feed types and TMPs (kPa)	Permeate flux (L/m^2 h)	Corrected permeate flux (L/m^2 h)	Water recovery (%)	Corrected specific flux (L/m^2 h/kPa)	Chemical cleaning frequency
MF permeate feed					
1,000	27.96	32.58	14.33	0.0325	1
2,500	53.93	59.45	31.65	0.0237	
4,000	73.75	79.80	40.39	0.0199	
UF Permeate feed					
1,000	31.02	33.80	13.01	0.0338	1
2,500	57.20	58.96	24.89	0.0235	
4,000	80.35	77.90	35.40	0.0194	
MBR permeate feed					
1,000	25.24	27.31	10.67	0.0273	4
2,500	29.03	29.20	12.57	0.0116	
4,000	24.52	24.74	11.09	0.0061	
GMF filtered feed					
1,000	21.23	22.42	9.10	0.0224	2
2,500	32.17	32.71	13.93	0.0130	
4,000	35.23	35.10	15.58	0.0087	

4,000 kPa than the 2,500 kPa. Similarly, the higher water recovery percentage was recorded in the TMP of 2,500 kPa and lowest at the TMP of 1,000 kPa, but after approximately 180 min of operation, water recovery percentages at TMP of 4,000 kPa drop below than the TMP of 1,000 kPa (Fig. 2).

The experimental results showed that the higher total hydraulic resistance (R_t) was obtained at a TMP of 4,000 kPa which increased rapidly with the time of operation. While in case of lowest TMP of 1,000 kPa, the total resistance was low and it increased at a lower rate (Fig. 3). These results might indicate that the more foulants are deposited while running at the higher TMP than the lower TMP. Further, with each experiment, the total hydraulic resistance at $t = 0$ increased. This increase represents the irreversible fouling. The higher rate of foulants deposition at higher TMP was also demonstrated by some researchers while running the RO with various concentrations of feed [16].

In the case of MBR permeate as the feed to the RO system, the permeate flux did not increase proportionally with applied TMPs, whereas MF, UF, and GMF effluents as feed to the RO system, the permeate fluxes were increased proportionally with applied TMPs (Table 3). In terms of corrected specific permeate fluxes, the higher the TMP, lower the corrected specific fluxes were recorded in all cases. The chemical cleaning was performed as according to previously described standard procedure on the basis of the reduction of the permeate flow rate (details in Section 2.4). From the results, it showed that the higher chemical cleaning frequency reported in the MBR permeate feed RO followed by GMF filtered feed RO, whereas lowest was reported in the both MF and UF permeate feed RO (Table 3).

3.2. Performance in terms of reduction in physical and chemical PFWQPs

The effectiveness of the membrane filtration processes in the reduction of the physical, inorganic non-metallic and aggregated organic constituents presents in the feeds were evaluated by the rejection

Table 5
Physical PFWQPs values and reduction percentages of MBR permeate feed RO

Sample types and TMPs (kPa)/Time (h)	Physical PFWQPs						
	Temperature (℃)	TSS (mg/L)	Turbidity (NTU)	Absorption (UV_{254nm})	TDS (mg/L)	EC (μs/cm)	IS (mg/L)
Feed							
1,000 kPa/1 h	21.92	ND[b]	0.35	0.100	738.10	1476.20	0.023
1,000 kPa/4 h	24.12	ND	0.37	0.100	758.60	1517.20	0.024
2,500 kPa/1 h	24.62	ND	0.38	0.100	763.30	1526.60	0.024
2,500 kPa/4 h	27.10	ND	0.41	0.100	789.70	1579.40	0.025
4,000 kPa/1 h	25.22	ND	0.48	0.104	793.30	1586.60	0.025
4,000 kPa/4 h	28.22	ND	0.55	0.102	828.50	1657.00	0.026
Permeate							
1,000 kPa/1 h	21.80	ND	0.11	0.006	11.3	22.60	0.006
1,000 kPa/4 h	23.72	ND	0.10	0.011	14.8	29.60	0.011
2,500 kPa/1 h	24.40	ND	0.09	0.006	13.8	27.60	0.006
2,500 kPa/4 h	26.45	ND	0.10	0.010	21.0	42.00	0.010
4,000 kPa/1 h	24.65	ND	0.10	0.006	20.5	41.00	0.006
4,000 kPa/4 h	27.15	ND	0.10	0.010	35.0	70.00	0.010
R%[a]							
1,000 kPa/1 h	0.54	NA[c]	68.57	94.00	98.46	98.46	73.91
1,000 kPa/4 h	1.65	NA	72.97	91.00	98.04	98.04	54.16
2,500 kPa/1 h	0.89	NA	76.31	96.00	98.19	98.19	75.00
2,500 kPa/4 h	2.39	NA	75.60	90.00	97.34	97.34	60.00
4,000 kPa/1 h	2.26	NA	79.16	94.23	97.41	97.41	76.00
4,000 kPa/4 h	3.79	NA	81.81	90.19	95.77	95.77	61.53

[a]Reduction percentage (R%) calculated according to Eq. (7); [b]ND = not detectable with used method; [c]NA = not available.

coefficients, which were referred to PFWQPs. As previously discussed, both physical and chemical PFWQPs selected in the present work were: physical (total suspended soilds [TSS], turbidity [NTU], absorption (UV_{254nm}), total dissolved solids [TDS], EC, and ionic strength [IS]), chemical (TN, total phosphorus [TP], COD, total carbon [TC], inorganic carbon [IC], and TOC). The rejection coefficient for the specific case of TSS was defined by:

$$f_{TSS} = (TSS_F - TSS_P)/TSS_F \quad (6)$$

where f_{TSS} is rejection coefficient of TSS, $TSS_{F,}$ and TSS_P represent the TSS in the feed and permeate samples, respectively. Similar equations were used for remaining rejection coefficients ($f_{Turbidity}$ for turbidity, fUV_{254nm} for UV_{254nm}, f_{TDS} for TDS, f_{EC} for EC, f_{IS} for IS, f_{TN} for TN, f_{TP} for TP, f_{COD} for COD, f_{TC} for TC, f_{IC} for IC and f_{TOC} for TOC. These rejection coefficients were determined at with different feeds, TMPs and operation times. Further, the reduction percentages of the PFWQPs were determined by applying Eq. (7) given below

$$\text{Reduction percentage (R\%)} = (C_F - C_P)/C_F \times 100\% \quad (7)$$

where R% is reduction percentage, C_F is feed concentration, and C_P is permeate concentration

3.2.1. Physical PFWQPs values and reduction percentages

The largest particles in secondary effluent would be measurable as SS; which is the broadest measure of fouling potential for RO membranes. The RO would be best protected from fouling if SSs were completely absent or zero [6]. The physical PFWQPs values and their reduction percentages were given in Table 4.

From the past research studies, it has been found that turbidity reduction percentage depends on the types of membrane systems used. For example, MF can remove more than 97% of turbidity and RO can remove more than 99% of turbidity [6].

The results of current experiments demonstrated that MBR permeate feed RO can removed 68.57–81.81% of turbidity (Table 4). As the MBR industry utilizes turbidity as the test for membrane integrity and the research is occurring for the use of turbidity as a surrogate for fecal coliform removal [17]. This means that higher percentages of turbidity removal may reflect the lower percentages of the fecal coliform.

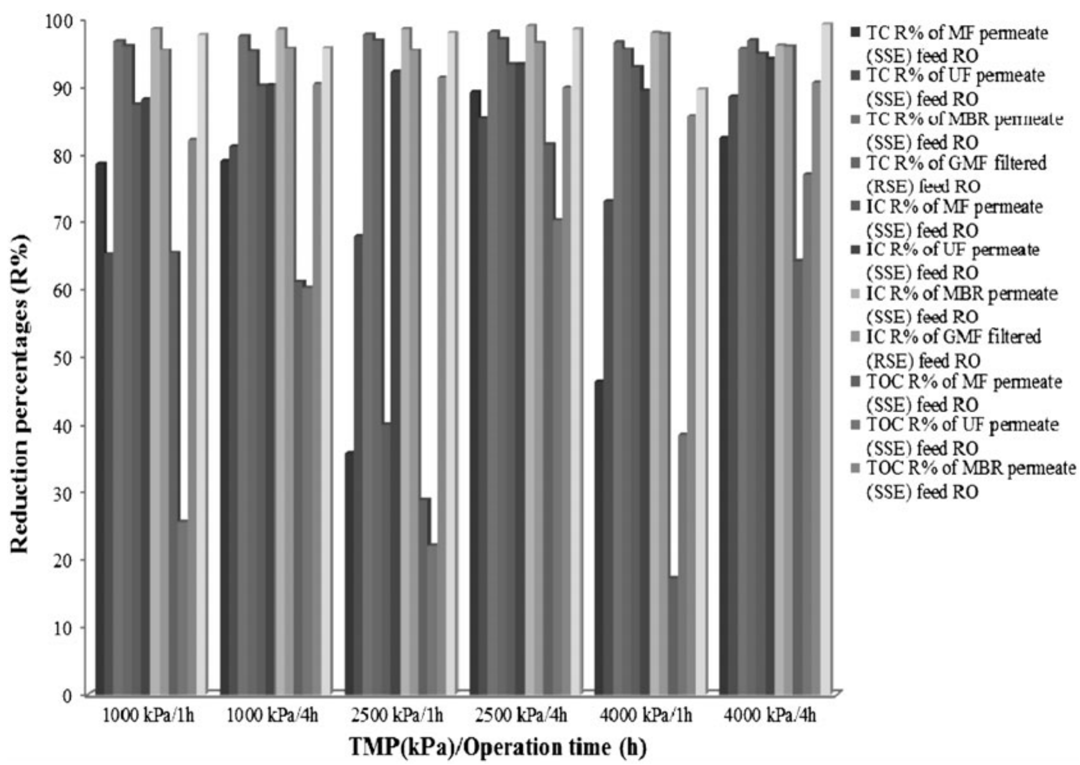

Fig. 4. Performance of BWRO30 2540 at various feeds in terms of chemical PFWQPs reduction.

Like TOC and dissolved organic carbon (DOC), UV_{254nm} absorbance is commonly used to characterize the organic constituents in a water sample. As DOC removal is very important for reducing the organic/biological fouling, it is an effective indicator to check the efficiency of treatment plant. The residual DOC after treatment will react with disinfectants which will result in the formation of undesirable disinfectant by-products and ultimately become complex to remove during further treatment.

The experimental results in most cases demonstrated that more than 90% of UV_{254nm} was removed by RO that was fed with MBR permeate (Table 4). The observed results indicate that, ultraviolet absorbance in 254 nm (UV_{254nm}) removal was highest at TMP of 2,500 kPa in 1 h (Fig. 4). In all cases, more than 95% of EC was reduced (Table 3); same as TDS reduction percentages (Table 4).

3.2.2. *Chemical PFWQPs values and reduction percentages*

Organic removal is one of the more important applications of membrane processes as they can reliably remove all kinds of organic matter compared to other treatment methods. In general, organic matter (OM) can be categorized into particulate organic matter (POC) (particles with size more than 0.45 μm) and expressed in terms of SSs and turbidity and dissolved organic matter (DOC) (particles with size less than 0.45 μm). TOC and DOC can be used as indirect measures of organic foulants. Since treatment with high-pressure membranes requires feed water

Table 6
Chemical PFWQPs values and reduction percentages of MBR permeate feed RO

Sample types and TMPs (kPa) /Time (h)	Chemical PFWQPs values and reduction percentage (R%)[a]								
	Inorganic non-metallic constituents				Aggregate organic constituents				
	pH	TN (mg/L)	TP (mg/L)	Dissolved O_2 (mg/L)	COD (mg/L)	TC	IC (mg/L)	TOC (mg/L)	UV_{254nm} (abs254/cm)
Feed values									
1,000 kPa/1 h	8.87	30.20	14.86	7.54	10.60	102.63	91.49	11.17	0.100
1,000 kPa/4 h	8.87	32.60	15.38	6.96	11.60	105.00	92.20	12.78	0.100
2,500 kPa/1 h	8.82	32.80	15.36	7.12	11.40	106.63	94.63	11.97	0.100
2,500 kPa/4 h	8.85	33.60	15.90	7.02	9.80	108.87	98.60	10.26	0.100
4,000 kPa/1 h	8.91	32.40	15.94	6.88	12.20	111.87	99.25	12.63	0.104
4,000 kPa/4 h	8.73	34.00	14.38	6.56	9.60	119.24	108.44	10.75	0.102
Permeate values									
1,000 kPa/1 h	7.61	5.0	0.35	7.30	7.80	3.38	1.37	2.01	0.006
1,000 kPa/4 h	7.41	4.2	0.24	7.16	7.60	2.68	1.43	1.24	0.011
2,500 kPa/1 h	7.17	5.0	0.26	6.94	7.60	2.47	1.42	1.05	0.006
2,500 kPa/4 h	7.37	6.6	0.31	6.66	8.00	2.11	1.06	1.05	0.010
4,000 kPa/1 h	7.07	6.6	0.34	6.60	7.80	3.87	2.05	1.82	0.006
4,000 kPa/4 h	7.08	9.0	0.40	6.66	7.60	5.28	4.26	1.02	0.010
R%[a]									
1,000 kPa/1 h	14.20	83.44	97.64	3.18	26.41	96.70	98.50	82.00	94.00
1,000 kPa/4 h	16.45	87.11	98.43	−2.87	34.48	97.44	98.44	90.29	91.00
2,500 kPa/1 h	18.70	84.75	98.30	2.52	33.33	97.68	98.49	91.22	96.00
2,500 kPa/4 h	17.72	80.35	98.05	5.12	18.36	98.06	98.92	89.76	90.00
4,000 kPa/1 h	20.65	79.62	97.86	4.06	36.06	96.54	97.93	85.58	94.23
4,000 kPa/4 h	18.90	73.52	97.12	−1.52	20.83	95.57	96.07	90.51	90.19

[a]Reduction percentage (R%) calculated according to Eq. (7).

with essentially no SSs, pre-treatment should result in a TOC that is same as the DOC.

Specifically, removal effectiveness of organic matters (OM) from biologically treated secondary effluent (BTSE) is strongly influence by the concentration of DOC, MW distribution and the type of micro-pollutants. For this reason, DOC is given more weight than particulate organic carbon (POC) during the application of pretreatment as some of these even escapes from membrane processes. The DOC removal from BTSE significantly depends on membrane processes used. The DOC (in terms of BOD/COD) removal of MF, MBR, UF, NF, and RO was 11, 75, 45, 86, and 92%,respectively [18,19]. These suggest that a significant portion of organic matter in the BTSE consists of low MW compounds much smaller than 20 kDa.

Based on the experimental results of this study, the MBR removed 97.86% of COD, and 12.63% of TP and 41.17% of TN.whereas MBR permeate feed BWRO reduced 28.24% COD, 97.90% TP, and 81.46% TN (Table 5). In addition, more than 95% of TC was removed at all TMPs during all hours of operations (Table 5).

The TP reduction percentages were almost similar (97–98%) at all TMPs. However, there are significant differences were observed in TN reduction percentages at various TMPs and the duration of filtration. In all TMPs and durations, inorganic carbon reduction percentages were higher than the total carbon and TOC removal (Table 5).

Kim et al. found that MF can removed 11% of DOC from BTSE of North Buffalo WWTP USA which was almost similar to the DOC removal capacity of UF (15%) [20]. Whereas Duin et al.'s experimental results showed that UF removed 10% of DOC as COD while treating BTSE at Driebergen, the Netherlands [21]. This experimental result demonstrates that MBR was able to remove about 51% of COD, whereas BWRO was able to remove 18.36–36.06% of COD from MBR permeate (Table 5). Most of the experimental results showed MBR system can removed more DOC (as BOD/COD) than the MF and UF which was in the range of 70-98% [17] while treating BTSE from various WW treatment plants.

In general, MF removes 5–10% of OM, UF removes up to 40–60%, NF removes more than 80% and the RO removes more than 90% [5]. Results of the experiments

Table 7
Class A recycle water quality, applied treatments processes and acceptable uses

Class	Water quality objectives	Treatment process[a]	Acceptable uses[b]
A	<10 *E. Coli* org/100 mL	Tertiary treatment & pathogen reduction with sufficient log reduction to achieve bacteriological parameters	Raw human food crops exposed to the recycled water (e.g. tomatoes, lettuce)
			Livestock drinking (excluding pigs)
			Dairy cattle grazing/fodder
	<2 NTU turbidity		Cooked/processed human food or selected crops not directly exposed to the recycled water
	<10 mg/L BOD		Grazing and fodder for cattle, sheep, horses, goats, alpacas etc. (excluding pigs)
	<5 mg/L SSs		Non-food crops e.g. woodlots, turf, flowers
	pH 6–9		Residential uses e.g. toilet flushing, washing machine, gardens
	1 mg/L Chloride residual		Unrestricted public access areas e.g. sporting facilities, botanical gardens, water features, golf courses
			Open industrial systems e.g. industrial laundry, carwashes
			Road construction

[a]EPA Publication 730, Guidelines for Environmental Management; Disinfection of Reclaimed Water 2003.
[b]EPA Publication 464.2 Guidelines for Environmental Management; use of Reclaimed Water, 2003.

conducted showed that the performance of RO in terms of the removal of organic matters (TC) depended on the types of pre-treatment permeates as the feed for RO, for example in case of MF permeate as feed for RO (75–92%), UF permeate as feed for RO (75–95%), MBR permeate as feed for RO (95–98%) and GMF permeate as feed for RO (95–97%), which clearly showed that all of pre-treated RO feed removed more than 92% of organic pollutants (Fig. 4). Moreover, in all permeate feeds, IC removal percentages was greater than TOC removal except for some cases (GMF filtered permeate as feed for RO) (Fig. 4).

In Australia, the water reclaimed from municipal wastewater are classified according to water quality and brief details of Class A recycle water with water quality, applied treatment process and acceptable uses are given in Tables 6 and 7.

The experimental results demonstrated that the RO permeate quality parameters in terms of turbidity, SS, and pH were above the Class A category of Australian recycle water (Table 6). In addition, results showed that the RO permeate quality in terms of conductivity, turbidity, organic and nutrients contents could meet the water quality requirements for many potable and non-potable reuse applications (Tables 4 and 5).

The higher corrected permeate flux as well as water recovery percentages were recorded in the MF permeate feed RO at TMP of 4,000 kPa, whereas the lowest was recorded in the MBR permeate feed RO within same TMP (Table 3). This may be due to less foulants present in the MF permeate than MBR permeate. In all cases (except MBR permeate), corrected permeate fluxes increases with the application and results showed that higher the TMPs then higher the corrected permeate fluxes. This phenomena of RO towards MBR permeate need to be further studies to get the clear explanation of this situation. The results showed that corrected specific permeate fluxes were decreases with the increases in TMPs. In terms of corrected permeate fluxes and water recovery percentage, MF permeate shows higher values than pre-treated feeds. The most physical and chemical PFWQPs of MBR permeate feed RO were above the class A reclaimed water which showed the broadening of the reuse options by enhancing the reclaimed water quality.

4. Conclusion

The results of pilot-scale trials illustrated that MBR/RO as well as MF/RO, UF/RO, GMF/RO are able to produce higher quality reclaimable water from the raw agricultural sewage and secondary effluent, respectively. The laboratory test results from comprehensive physical, chemical analysis in these laboratory and pilot-scale filtration experiments showed that the quality of RO effluents meet the requirements of the potable and non-potable reuse options. From the results, it demonstrated that RO feed with MBR permeate was required frequent chemical cleaning than the other pre-treated effluents in order to maintain the required rate of product water. One of the reasons for this frequent chemical cleaning was due to higher total organic contents as well as TN in the MBR permeate. Permeate fluxes and water recovery rates of the RO feed with MBR permeate were found lower than for RO with other pre-treated effluents. These results needs to be further evaluated through field trials.

Symbols

A_{system}	—	surface area of membrane system (m^2)
C_F	—	feed concentration
C_P	—	permeate concentration
F	—	rejection coefficient
f_{TSS}	—	rejection coefficient of TSS
J	—	permeate flux ($L/m^2 h$)
P_C	—	concentrate/retentate pressure (kPa)
P_F	—	feed pressure (kPa)
P_P	—	permeate pressure (kPa)
ΔP	—	trans-membrane pressure (kPa)
Q_p	—	permeate flow (L/h)
Q_p	—	permeate flow rate (L/h)
Q_f	—	feed flow rate (L/h)
R%	—	reduction percentage
R_t	—	total hydraulic resistance (m^{-1})
TMP	—	trans-membrane pressure (kPa)
μ	—	permeate viscosity (Pa.s)
WR%	—	water recovery percentage

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