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Research article

Performance of electrodialysis reversal and reverse osmosis for reclaiming wastewater from high-tech industrial parks in Taiwan: A pilot-scale study

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A B S T R A C T

Wastewater reclamation is considered an absolute necessity in Taiwan, as numerous industrial parks experience water shortage. However, the water quality of secondary treated effluents from sewage treatment plants generally does not meet the requirements of industrial water use because of the high inorganic constituents. This paper reports experimental data from a pilot-plant study of two treatment processes—(i) fiber filtration (FF)-ultrafiltration (UF)-reverse osmosis (RO) and (ii) sand filtration (SF)—electrodialysis reversal (EDR)—for treating industrial high conductivity effluents from the Xianxi wastewater treatment plant in Taiwan. The results demonstrated that FF-UF was excellent for turbidity removal and it was a suitable pretreatment process for RO. The influence of two membrane materials on the operating characteristics and process stability of the UF process was determined. The treatment performance of FF-UF-RO was higher than that of SF-EDR with an average desalination rate of 97%, a permeate conductivity of 272.7 ± 32.0, turbidity of 0.183 ± 0.02 NTU and a chemical oxigen demand of <4.5 mg/L. The cost analysis for both processes in a water reclamation plant of 4000 m^3/d capacity revealed that using FF-UF-RO had a lower treatment cost than using SF-EDR, which required activated carbon filtration as a post treatment process. On the basis of the results in this study, the FF-UF-RO system is recommended as a potential process for additional applications.

1. Introduction

Fresh and clean water is becoming scarce in many countries as a consequence of rapid urbanization in conjunction with poor water management practices and climate change. Approximately one-fifth of the world's population faces water scarcity. By 2030, half of the world is predicted to be under water-stress conditions (United Nations, 2007). To overcome this crisis, alternative water sources i.e, seawater and wastewater have been explored (Mohammadi and Kaviani, 2003; Chuang et al., 2005; You et al., 2008; Chang and Ma, 2012).

Compared with seawater desalination, reusing and recycling sewage from wastewater treatment plants (WWTPs) are more technically and economically feasible. In addition, water reuse helps in reducing emissions of pollutants into the environment, as well as in reducing consumption of natural water resources. Influents in wastewater reclamation plants often require at least a secondary treatment, which is followed by various methods of water reclamation. According to United States Environmental Protection Agency wastewater effluent discharge standards, the quality of wastewater effluent from secondary WWTPs is usually sufficient for dust control, toilet flushing, landscaping and crop irrigation (Chang and Ma, 2012). However, these effluents requires additional advanced purification processes for industrial process water and cooling use.

In general, high conductivity wastewater is a key parameter for industrial water reuse as it contains high salt concentrations; thus, utilization of this water can easily lead to the information of scales and corrode the surface of the system pipeline or vessel. Several studies have shown that reverse osmosis (RO) and electrodialysis reversal (EDR) are promising treatment processes for removing

Abbreviations: CIP, Cleaning in place; CEB, Chemically enhanced backwash; UF, Ultrafiltration; RO, Reverse osmosis; FF, Fiber filter; EDR, Electrodialysis reversal; CA, Cellulose acetate; PVC, Polyvinyl chloride; SF, Sand filtration; COD, Chemical oxygen demand; TDS, Total dissolved solids; SDI, Silk density index.

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dissolved organic compounds and ionic pollutants (Wilf and Alt, 2000; Xing et al., 2000; Petala et al., 2006; Hsu et al., 2012; Chon et al., 2013a,b).

RO is a wastewater purification process that separates the solvent from the solutes through pressure differences. RO has been extremely effective in removing dissolved matter in municipal wastewater (Tang et al., 2016) and in the wastewater from various industries such as pulp and paper (Gönder et al., 2011), pharmaceutical (Ravikumar et al., 2014), dairy and food (Salehi, 2014), textile (Kim et al., 2005; Li et al., 2014; Holkar et al., 2016), and steel (Colla et al., 2016).

EDR is a process where electric current causes the dissolved ions, to migrate through an electrodialysis stack comprising alternating layers of cationic and anionic ion exchange membranes. EDR has been utilized for treating various industrial wastewater (Chao and Liang, 2008; Hsu et al., 2012; Scialdone et al., 2013, 2014a,b,c). The EDR process has also been used to produce renewable energies (Turek and Bandura, 2007; Cusick et al., 2012). Scialdone et al. (2014a,b,c) produced the electricity used to treat wastewater containing chromium pollutants through the EDR process. The same group generated the electric energy used to treat contaminated by the organic pollutant Acid Orange 7 (Scialdone et al., 2015).

Both RO and EDR treatment processes are extremely sensitive to membrane fouling; thus, an adequate pretreatment for RO and EDR processes must be provided to produce high quality of feed water for a stable process operation.

Numerous treatment processes are widely used to remove colloids and dissolved organic matter in secondary treated effluents. These processes include coagulation, sand filtration (SF), activated carbonfiltratio (Freeman et al., 2001; Muñoz et al., 2008) microfiltration (MF) and ultrafiltration (UF). With regard to the pretreated water quality, MF and UF are the preferred options to conventional media filtration (Qin et al., 2002; Bohdziewicz et al., 2003; Tomaszewska et al., 2005; Petrinic et al., 2015). The performance of these treatment systems is influenced by the characteristics of raw wastewater, the membrane materials, and other operating parameters such as feed flow rate. Yamato et al (2006) observed the membrane fouling in membrane bioreactor (MBR) system that used two different polymeric. They found that or MBRs used for treating municipal wastewater, polyvinylidene fluoride (PVDF) could prevent irreversible membrane fouling to a greater extent compared with polyethylene. They explained that the reversible fouling for the PVDF membrane might be related to an increase in the submicron size of organic matter composed mainly of carbohydrates, whereas dissolved organic matters may be responsible for the irreversible fouling.

In the present study, we evaluated two processes for reclaiming wastewater from industrial parks: (i) fiber filtration (FF) UF RO and (ii) SF EDR. Several experiments were conducted to indentify which process delivered higher performance in terms of the process stability and removal efficiency. On the basis of the filtrate quality and cost analysis, a suitable wastewater reclamation system was suggested for additional applications.

2. Materials and methods

2.1. Xianxi wastewater treatment plant

Fifty-five industrial (WWTPs) operated in Taiwan. One of them is Xianxi WWTP, which is located in Changhua coastal industrial park in northern Taiwan. This WWTP applies activated sludge process to treat both rainwater and industrial wastewater from spinning processes, chemical industries, and metal processors. After the chlorine disinfection process, part of the treated wastewater is reused within the industrial park as low quality reclaimed water and the rest is discharged to the environment. However, water utilization from this source has become problematic because of the high concentration of salts and ions. This high concentration may be ascribed to the presence of sodium chloride in the wastewater. In addition, a long-term disposal may cause environmental impacts on the receiving water bodies, ground water, and soil. The average electrical conductivity of the industrial effluent was 7.3 mS/cm (Table 1) which is higher that reported in the literature (Chuang et al., 2005; López-Ramírez et al., 2006; Chao and Liang, 2008). Bauder et al. (2014) reported that irrigation water with conductivity greater than 0.75 mS/cm had potential to reduce crop yield.

2.2. Wastewater reclamation process: pilot-scale test

Two wastewater reclamation processes based on different treatment technologies of RO and EDR were examined. These processes can remove organic ions and improve the quality of the reclaimed water for sustainable water reuse within the industrialpark. The treatment performance and operating stability of both processes were compared under various operating conditions. Fig. 1 diagrams a flow schematic of a pilot-plant study for two treatment processes. Table S1 (supplementary information) indicates the characteristics and design control parameters for each treatment unit.

2.2.1. Operation of the fiber filtration-ultrafiltration- reverse osmosis process

Secondary effluent typically contains a wide variety of particulates that are responsible for membrane fouling. To minimize this effect, three filtration processes SF, FF and hollow-fiber ultrafiltration UF were tested for turbidity removal. Influent and effluent turbidity concentrations, water flow, and the operating pressure were monitored during the experiment, to determine a suitable pretreatment process for RO. When the turbidity removal decreased considerably or the operating pressure drop reached 2 kg/cm^2, the treatment systems were automatically backwashed with water and air. An additional step of chemical cleaning using 100 mg/L sodium hypochlorite (NaOCl) and 0.05% w/v sodium hydroxide (NaOH) was applied for the UF membrane after the backwash process.

The next step was to assess the influence of membrane materials and process operations (e.g. operating flux and cleaning frequency) on the water filtrate produced from the UF process. Two types of membranes (supplied by China) were used: (i) polyvinyl chloride

Table 1
Quality of the effluent water from the Xianxi WWTP (number of samples = 7).

Parameters	Min–max	Avg ± SD
pH	7.7–8.2	7.9 ± 0.20
Conductivity (mS/cm)	5.9–8.1	7.3 ± 0.83
Turbidity (NTU)	1.0–8.5	4.7 ± 2.87
TDS (g/L)	3.6–4.6	4.2 ± 0.39
COD (mg/L)	22.1–63.1	41.5 ± 15.40
TOC (mg/L)	3.7–7.1	5.5 ± 1.29
NH_4^+-N (mg/L)	0.05–0.16	0.1 ± 0.05
NO_3^- (mg/L)	1.0–52.4	21.3 ± 17.07
PO_4^{3-} (mg/L)	1.2–30.3	15.9 ± 10.26
Cl^-(mg/L)	1610–2210	2010 ± 224.05
Al (mg/L)	0.07–0.15	0.1 ± 0.03
Ca (mg/L)	57.2–72.5	63.9 ± 5.25
Fe (mg/L)	0.08–0.34	0.2 ± 0.13
Mg (mg/L)	103–129	118 ± 8.82
SiO_2 (mg/L)	13.4–20.0	16.8 ± 2.30
B (mg/L)	1.12–1.41	1.26 ± 0.12
SO_4^{2-} (mg/L)	60.3–579.0	435 ± 190.37

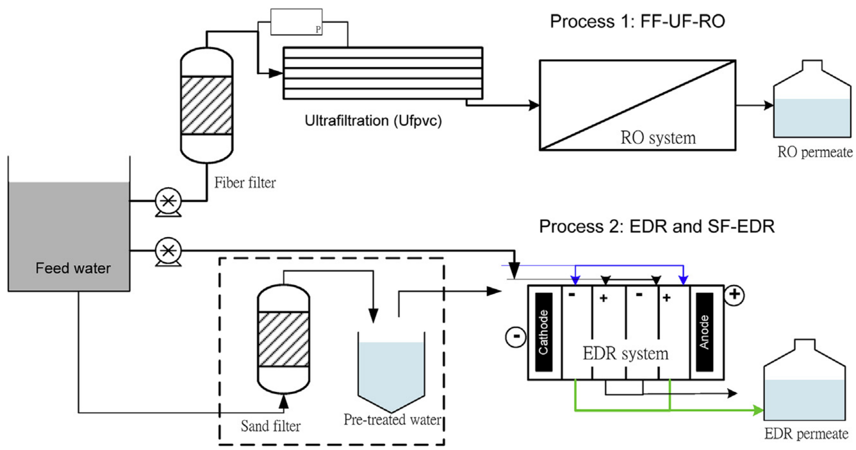

Fig. 1. Flow diagram of a pilot plant study: (i) FF-UF-RO and (ii) EDR with and without SF.

(PVC) LH3-0650-V (UFpvc) and (ii) cellulose acetate (CA) FN-20-VP-FUC1582 (UFca) for low and high water throughput, respectively. The UFpvc had a membrane surface area of 10 m^2, which was smaller than the 16 m^2 surface area of the UFca. During the experiment, the feed wastewater was pumped to the system with the flowrate ranging between 15 and 30 m^3/h and the flux was varied from 30 to 90 L/m^2 h (LMH) by altering the flowrate of the effluent. The transmembrane pressure (TMP) was recorded throughout the test; and when it increased to more than 2 kg/cm^2, the system would require cleaning-in-place (CIP).

For the RO operation, FF-UF was used as a pretreatment process to remove colloids and dissolved inorganic compounds from the secondary effluent before it was pumped to the RO system. The RO used in this experiment was a low fouling spiral wound membrane composed of a composite polyamide (LFC3-LD-4040, Nitto Group company) with an active area of 7.43 m^2. The pH of the feed water was maintained at a range of 6.7–7.0, and the system was operated at a pressure of 14.5 kg/cm^2 with a 50% recovery. For the membrane cleaning, 0.01 M each of NaOH and hydrochloric acid (HCl) were used.

2.2.2. Operation of the electrodialysis reversal system

The desalination efficiency for EDR was tested with and without a pretreatment process (i.e., SF). The wastewater from each of the following was used as the feed water for the EDR system: secondary clarifier, a discharge station, and an SF unit for treating the Xianxi secondary effluent. The EDR system was equipped with a stack of 40 membranes in series, with a total available membrane area of 3200 cm^2 and a maximum capacity of 24 m^3/d. The system was operated at 50–60% water recovery and 0.3% w/v for both NaOH and HCl solutions that were used as a cleaning agent. The membrane cleaning process was started when the permeate conductivity was greater than 0.8 mS/cm.

2.3. Analytical methods

Water turbidity was determined using a portable turbidity meter. The membrane flux and TMP were measured onsite daily. Water parameters, such as conductivity, chemical oxygen demand (COD), and dissolved organic carbon, were analyzed according to standard methods, by an accredited laboratory (SGS consultants, Taiwan). The characteristics, such as molecular weight distribution, of the wastewater effluent were measured using a high performance liquid chromatography (HPLC, LC-20 ATV, Shimadzu, Japan) equipped with an analytical grade column (TSK HW-50S, Toyo pearl, Japan), and coupled with an ultraviolet–visible spectroscopy detector (SPD-20A, Shimadzu, Japan), a fluorescence detector (Shimadzu RF-10AXL spectrofluorometric detector, Japan), and a total organic carbon (TOC) analyzer (Sievers 900 online TOC built-in IC remover, USA).

3. Results and discussion

The characteristic of substances in the secondary effluent from the Xianxi WWTP must be explored. This is to understand and assess the treatment process required to produce reclaimed water. Our preliminary studies (data not shown) reported that, the molecular size of substances in this effluent was distributed at 100, 1000, 1500, 3200 and 80,000 Da. Further measurement of the TOC and UV_{254} indicated that these substances are likely (i) aqueous salts (100 Da), (ii) aromatic proteins (1000–3200 Da) derived during the biological process of wastewater treatment, and (iii) microorganisms or refractory organic compounds with the C=C bond of insoluble organic compounds or intermediate by-products (80,000 Da) from the biodegradation of parent organic compounds in raw wastewater.

Other researchers found that microorganisms and suspended solid particles could easily foul the RO membrane. Therefore, pretreating the effluent prior to the RO process was necessary for the conductivity removal. In this study, the turbidity parameter was used as an indirect measure of colloids and solid particles in water. Table 2 indicates that the wastewater had a turbidity concentration that varied from 1.6 to 8.4; approximately 50% of the turbidity could be removed by a simple process of FF and SF. However, the turbidity level of the water filtrated was still high for the RO process (Chuang et al., 2005; Sahachaiyunta et al., 2002); further treatment was required. This would be UF because it could separate particulate matters from the filtered water with a removal efficiency of 97%. Although UF was the most effective pretreatment process for RO, the installation of FF or SF was also required because it could reduce organic load from the water and prevent the membrane from fouling.

3.1. Influence of membrane materials and operating condition during the ultrafiltration process

Physico chemical properties of membranes and operating conditions are critical parameters that influence membrane fouling in wastewater reclamation processes. The factors that substantially influence the deposition of foulants on the membrane during

Table 2
Turbidity removal efficiencies of different filtration processes.

Treatment process	No. of samples	Min. − max. (NTU)	Average (NTU)	Removal rate (%)
Secondary eff.	7	1.58–8.44	3.04	–
FF	7	0.59–2.41	1.26	52.7 ± 13.9
SF	2	1.35–1.45	1.40	42.1 ± 6.1
UFpcv	7	0.15–0.26	0.18	91.7 ± 4.7

filtration process are as follows: membrane surface morphology and surface charge properties of both the foulants and the membrane (Yamato et al., 2006; López-Ramírez et al., 2006). The adsorption of foulants on the membrane surface occurs when the charges of these two materials are different. In addition, operating conditions can cause strong considerable modifications of the membrane that affects its performance. In this study, the effects of PVC and CA membranes on the turbidity removal efficiency and the process stability of the UF process were examined at various levels of the operating flux. Fig. 2–4 present the data obtained in the experimental plant.

Fig. 2, illustrates that the increase of membrane flux increase (from 60 to 90 LMH) for the UFpvc decreased the turbidity removal rate (from 81.7% to 73.3%); and no significant change of the initial TMP values was observed until day 140. This suggests that the regular CIP of 10–12 days was sufficient to remove the solids accumulated on the membrane surface. However, from day 141, irreversible membrane fouling was evident observed as the TMP increased approximately two times its the initial value (0.6 kg/cm^2). Under this condition, the system is unable to maintain the maximum flux of 90 LMH without exceeding the TMP of 2 kg/cm^2 and damaging the membranes. Thus, the operating flux of 60 LMH was applied, and the membrane-cleaning program was performed every 16 days using a cleaning solution volume of 60 L (Table 3). Nevertheless, the turbidity removal rate worsened (63.5%), and the TMP reduction did not improve. This indicates that the actual membrane flux required for this system must be even lower. The treatment efficiency for the UF system improved to 72% when the permeate flux was controlled at 30 LMH. Effluent turbidity concentrations were attained at a range of 0.2–0.45 NTU.

For the CA membrane, variation of turbidity removal efficiencies in relation to the operating flux was larger than that for the PVC membrane (Fig. 3). The effluent turbidity of 0.17–0.81 NTU for the CA membrane is higher than the 0.25–0.65 effluent turbidity for the PVC membrane. This could be a result of the difference in the applied operating condition, membrane properties, or combined effects. When the system TMP was compared, CA was found to have a relatively low and stable TMP compared with that of PVC, suggesting that CA has low fouling potential. López-Ramírez et al. (2006), observed that the CA membrane surface was relatively smooth. Thus, it was more resistant to fouling. On the basis of these results, the CA membrane could operate at a higher flux with fewer frequency of membrane cleaning.

Table 3 and Fig. 4 imply that the quality of permeates produced

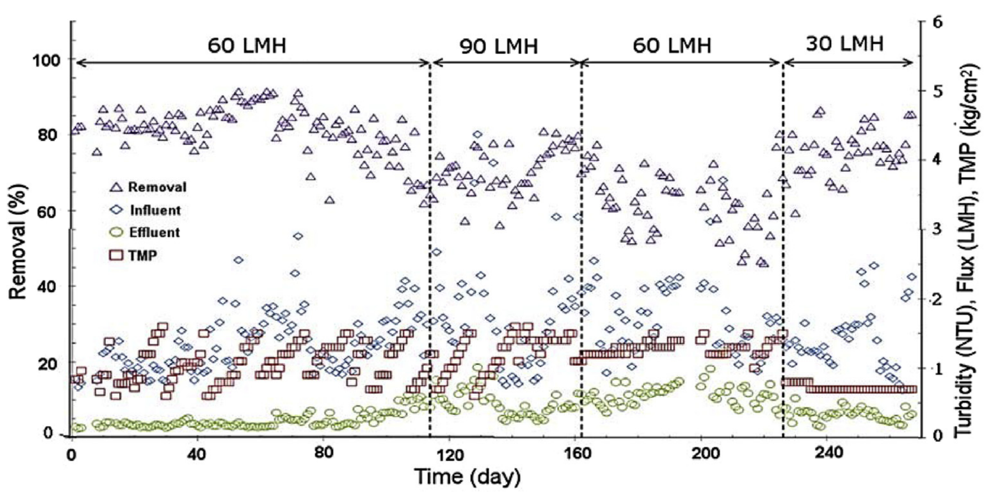

Fig. 2. Changes in the turbidity removal and flux for UFpvc under various conditions of **constant flux control**.

Table 3
Comparison of turbidity removal using different UF materials under various operating conditions.

Material	Flux (LMH)	Inf. turbidity (NTU)	Eff. turbidity (NTU)	Rev (%)	CIP vol (LPM)	CIP interval. (Day)
UFpvc	60	1.33	0.25	81.2	40	12
	90	1.91	0.51	73.3	40	10
	60	1.78	0.65	63.5	60	16
	30	1.31	0.36	72.5	40	26
UFca	75	1.32	0.17	87.1	40	13
	60	1.52	0.63	58.6	40	15
	90	1.68	0.78	53.6	40	13
	90	1.80	0.81	50.0	80	42

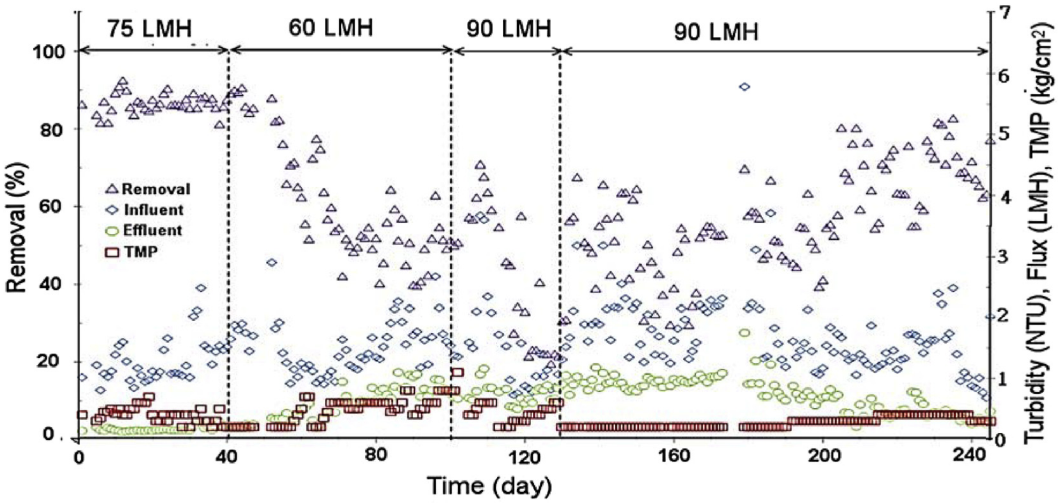

Fig. 3. Changes in the turbidity removal and flux for UFca under various conditions of **constant flux control**.

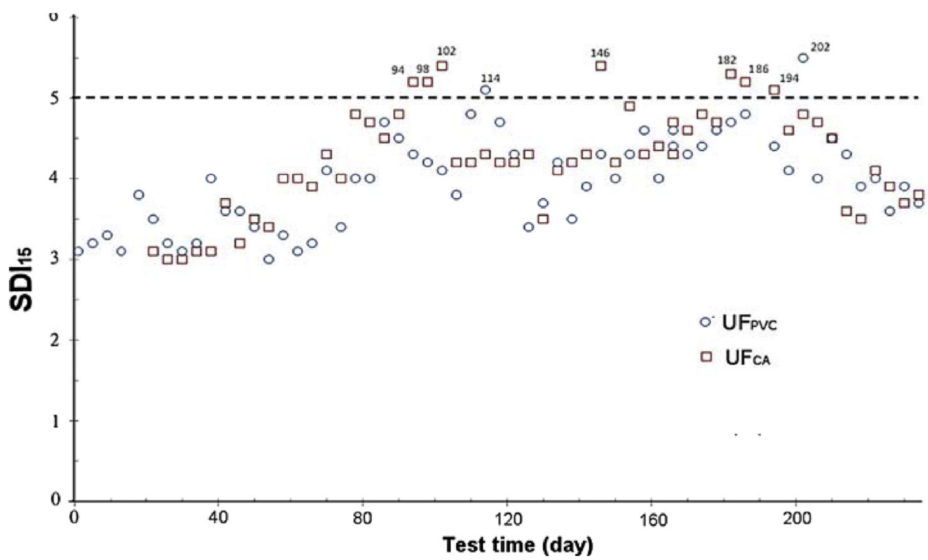

Fig. 4. SDI test results for UFpvc and UFca.

from UFpvc and UFca meets the RO feed water requirement. This suggests that both membranes could be used in a pretreatment process for RO. However, PVC is preferred because of its durability and low cost.

3.2. Operation of fiber filtration-ultrafiltration-reserve osmosis

The effluent from the FF-UF process, which had a turbidity concentration lower than 1 NTU, was used as the feed water for the RO operation. Experiments were divided in two stages according to the operation mode: (i) one-through mode from day 1–48 and (ii) internal flow recirculation mode with 50% water recovery from day 49–124.

Fig. 5 shows that RO could remove the influent conductivity at a high removal rate of 91.7% despite a double increase in the influent conductivity from 6.5 to 8.3 mS/cm to 8.9–15.2 mS/cm in the feed water on day 49. The system TMP increased after the RO concentrate was recycled on day 50. This could be related to scale formation on the membrane surface. A studies demonstrated that scaling in RO processes was associated with a high concentration of aluminum, calcium, silica, phosphate, and carbonate in the RO feed (Fritzmann et al., 2007). When the amount of these salts exceeded the saturation, they would precipitate and form a layer on the membrane surface, causing the membrane flux to decline and the TMP to increase. To minimize the scaling observed in this study, the RO system was cleaned with a solution of 0.01 M NaOH and 0.01 M HCl every 5–7 days. Fig. 5 indicates that the operating pressure of the system was maintained stable at 14.5 kg/cm^2 from day 60, and the permeate conductivity during the experimental period varied from 174 to 308 uS/cm, with the attained flux 18 LMH.

3.3. Operation of electrodialysis reversal with and without sand filtration

The desalination efficiency of the system was observed using different types of feed water: (i) water obtained from the secondary clarifier within day 1–17 (ii) water emitted from the discharge station within day 18–40, and (iii) water collected after SF within day 41–56. The pH of raw wastewater was maintained between 6.7 and 7.0 throughout the experiment. Fig. 6 indicates that the

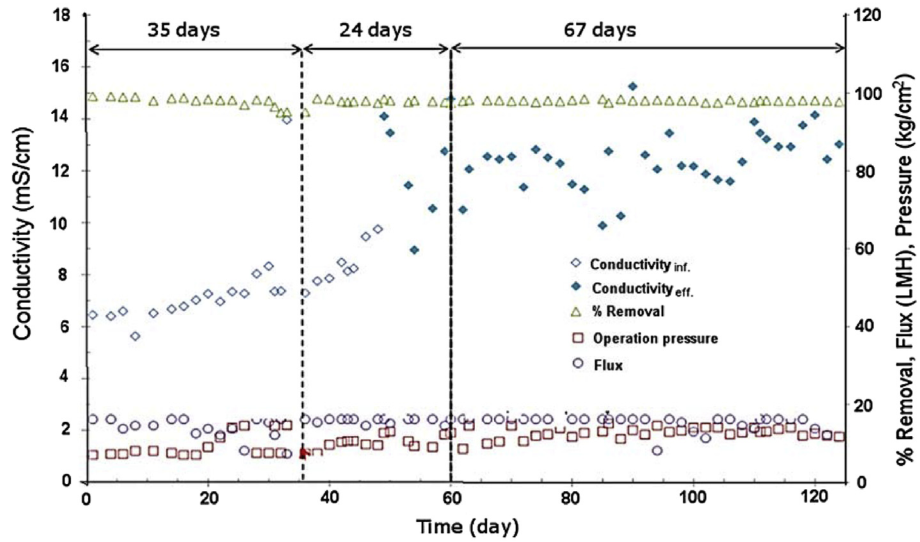

Fig. 5. Changes in the RO desalination efficiency and operating flux.

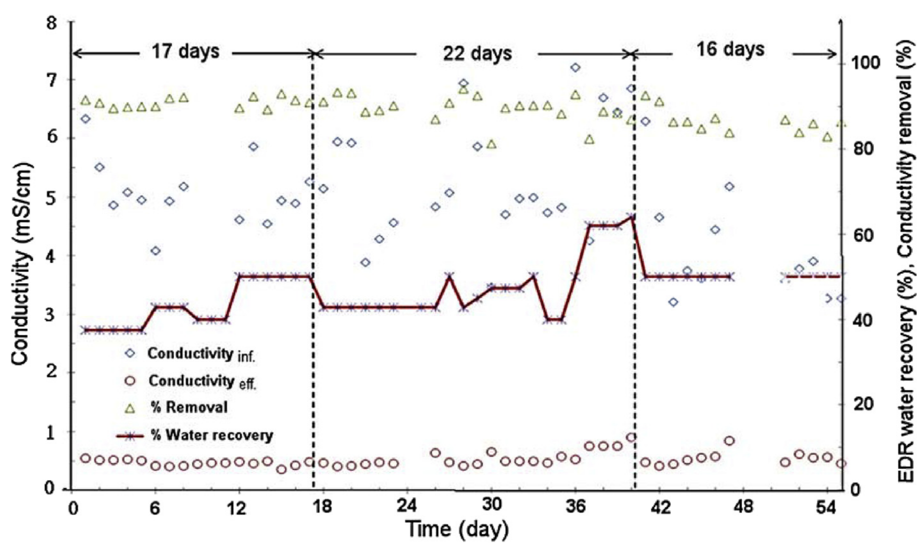

Fig. 6. Changes in the EDR desalination efficiency and operating flux (without SF within day 1–40 and with SF within day 41–56).

conductivity level of the EDR feed water obtained from different sources was similar; the concentration varied from 4.0 to 7.5 mS/cm. The treatment performance of EDR was stable with an average conductivity removal rate of 89.7% and a water recovery rate of 40–50%. These data suggest that unlike the RO process, EDR does not require a high quality of feed water. It can directly treat the secondary effluent from the Xianxi WWTP, and this approach will reduce the treatment cost for the wastewater reclamation process. However, particulate matters in the secondary effluent may accumulate on the EDR electrode, which could result in treatment performance reduction. The system required frequent cleaning to clean the membrane and maintain high treatment efficiency. As previously mentioned, EDR does not require extremely clean water; the application of SF as a pretreatment for this process could be sufficient to diminish the particulates from the water, produce homogeneous feed water, and prevent the EDR membrane from fouling. Fig. 6, illustrates that the effluent conductivity after the EDR process varied between 0.35 and 0.90 mS/cm, which is safe for the environment and crop irrigation.

3.4. Quality of permeate

Table 4 summarizes the removal efficiency for FF-UF-RO and SF-EDR processes. The results reveal that the FF-UF pretreatment process was excellent in removing turbidity from 6.03 ± 3.29 to 0.72 ± 0.60 NTU, with a removal efficiency of 83%. Approximately 25% of COD was also removed. However, TDS, conductivity, and chloride concentrations could not be diminished in this unit. Both RO and EDR processes had high treatment efficiency for ionic removal. In addition, surplus organic separation resulted in reduction of COD in the final effluent to a concentration lower than 4.5 mg/L for RO and 14.3 mg/L for EDR. Table 4 indicates that the FF-UF-RO process performed better than the SF- EDR process in terms of the treated wastewater quality for cooling water reuse.

3.5. Cost evaluation

Scaling up wastewater treatment system and commercializing developed processes require a cost analysis. Therefore, the cost

Table 4
Quality of the treated water from various treatment units.

Parameters	2nd effluent	FF + UF	FF-UF-RO	SF-EDR
pH	8.03 ± 0.21	7.87 ± 0.40	6.367 ± 0.5	6.9 ± 0.52
Turbidity (NTU)	6.03 ± 3.29	0.72 ± 0.60	0.183 ± 0.02	0.25 ± 0.05
Conductivity (μS/cm)	7373 ± 554.10	6870 ± 878.41	272.7 ± 32.0	595.7 ± 139.2
TDS (mg/L)	3943 ± 325.60	3647 ± 236.92	119.3 ± 4.70	339.7 ± 77.84
COD (mg/L)	37.23 ± 9.26	29.3 ± 13.40	<4.5	14.33 ± 4.62
NH_4^+-N (mg/L)	0.15 ± 0.02	0.076 ± 0.07	0.1 ± 0.001	0.09 ± 0.04
PO_4^{3-} (mg/L)	15.37 ± 6.97	13.67 ± 6.69	0.06 ± 0.01	2.43 ± 0.91
Cl^- (mg/L)	2137 ± 66.58	1887 ± 347.04	71.63 ± 26.0	97.37 ± 35.55
B (mg/L)	1.21 ± 0.08	1.14 ± 0.03	0.92 ± 0.10	1.07 ± 0.08
Al (mg/L)	0.10 ± 0.02	0.053 ± 0.04	<0.02	0.03 ± 0.01
Fe (mg/L)	0.25 ± 0.14	37.04 ± 64.05	0.03 ± 0.0	0.06 ± 0.05
Mg (mg/L)	117 ± 1.0	89.73 ± 27.71	0.34 ± 0.02	5.55 ± 2.90
Ca (mg/L)	64.4 ± 1.25	43.43 ± 25.21	1.03 ± 0.0	3.66 ± 1.82
SiO_2 (mg/L)	17.2 ± 1.31	185.9 ± 294.57	0.52 ± 0.0	14.33 ± 3.53
SO_4^{2-} (mg/L)	515 ± 19.92	474 ± 53.03	2.21 ± 0.6	88.33 ± 21.86

Table 5
Cost estimates for different wastewater reclamation treatment processes.

Costs	FF + UF_{PVC}	FF + UF_{PVC}-RO	SF-EDR
Electricity	0.05	0.19	0.16
Chemicals	0.02	0.05	0.07
Membrane replacement	0.06	0.22	0.28[a]
Electrical and mechanical maintenance	0.02	0.06	0.08
Others[b]	0.14	0.06	0.14
Subtotal	0.29	0.58	0.73
Total reclaimed water cost (USD)[c]	0.42	0.96	1.18

Note.
[a] Included activated carbon replacement fee.
[b] Included sludge handling fees, labor cost, insurance cost, and water sample analysis fee.
[c] Estimations based on water reclamation plant with 4000 m^3/d capacity.

analysis of the two investigated processes was appraised. Table 5 tabulates the data. The addition of an activated carbon filtration after the EDR process was proposed because the conductivity of effluents from the EDR unit occasionally exceeded the water requirement for cooling water application purposes. The operating cost for the combined FF-UF-RO process was approximately USD0.58 or NTD18.3 per ton of reclaimed water, which is lower than the operating cost of USD0.73 (NTD23.2) per ton of reclaimed water for the SF-EDR process. Hsu et al. (2012) installed a pilot plant in the Futian Municipal WWTP in Taichung city, Taiwan using SF-UF-RO and SF-EDR processes for wastewater reclamation. Subsequently, they performed a cost analysis for both processes and reported that the cost required for the SF-EDR process (USD0.57) was lower than that for the SF-UF-RO (USD0.65) process. However, the filtrate quality was extremely poor in the SF-EDR process. In this present case of our FF-UF-RO process, we have observed promising results in terms of high permeate quality. From the comprehensive cost evaluation studies, we conclude that the FF-UF-RO process can be selected as the best water reclamation procedure, which should be considered for future full-scale water reclamation plants.

4. Conclusions

After conducting long-term tests on the desalination efficiency of RO and EDR processes, we reached the following conclusions:

1) FF + UF process could be used as a pretreatment process for both RO and EDR, as it was effective for turbidity removal, with an overall treatment efficiency of 91.7%.

(2) Although two different UF materials generated different operating characteristics, no difference in the silk density index (SDI_{15}) of the produced water was detected, indicating that they had robust protective effect on the subsequent RO process.

(3) Under the same treatment conditions, RO could remove 97.9% of the influent conductivity, whereas EDR could remove only 89.1% of the conductivity.

(4) The operating costs of FF-UF-RO and SF-EDR were assessed and calculated to be USD 0.70 and USD 0.73 per ton of reclaimed water, respectively. Therefore, FF + UF_{PVC} + RO is a more efficient process for treating the wastewater from the Xianxi WWTP.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.11.001.

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