Recycling the wastewater of the industrial park in Northern Taiwan using UF-RO system: *in-situ* pilot testing and cost analysis

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ABSTRACT

In Taiwan, every industrial park equips a wastewater treatment plant (WWTP) to collect wastewater streaming from all the factories. These effluents, though showing high total dissolved solids (TDS) and fluctuating composition, would be a valuable water resource for industrial use after large scale purification, especially in the drought seasons. In this study, a pilot plant was installed for reclaiming the effluents from the industrial park WWTP through the membrane process. A modified spiral-wound ultrafiltration (UF) membrane with backwash function was utilized for the pretreatment of the reverse osmosis (RO) system. Evaluation results showed that the pilot plant was performing stably during the two-month operation. After the RO desalination, the quality of the reclaimed water basically met the requirement standards of intermediate-pressure boiler feedwater (150 ~ 750 psig) of the Environmental Protection Agency, United States (USEPA). The backwashable spiral wound UF membrane provided suitable water quality for RO influent (SDI < 4) and helped reduce the cost compared to using hollow-fibre UF membrane. The total cost of recycling one-ton effluent included US$ 0.35 for construction and US$ 0.45 for operation/maintenance.

Key words | backwashable spiral wound UF, cost analysis, industrial park, reclaimed water

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ACRONYMS AND ABBREVIATIONS

COD	Chemical oxygen demand
EPA	Environmental Protection Agency
MWCO	Cut-off molecular weight
O&M	Operation/maintenance
PCC	Public Construction Council (Taiwan)
PVDF	Polyvinylidene difluoride
RO	Reverse osmosis
SDI	Silt density index
SF	Sand filter
SSS	Suspended solids
TDS	Total dissolved solids
TMP	Trans-membrane pressure
UF	Ultrafiltration
WRA	Water Resource Agency (Taiwan)
WWTP	Wastewater treatment plant

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INTRODUCTION

In 2000, Taiwan's annual water demand was 18 billion m^3. Nearly 2 billion m^3 (11%) was for industrial purposes, a figure expected to grow to 2.5 billion m^3/year over the next decade (Water Resource Agency 2002). Considering the increasing difficulties of building a new reservoir in Taiwan, the Water Resource Agency (WRA) is now exploiting 'non-traditional' water resources, including rainwater catchments, seawater desalination and reclamation of domestic and industrial wastewater. Among these alternatives, recycling industrial wastewater efficiently on a large scale can provide a relatively stable resource, helping meet this rapidly growing demand. In Taiwan, factories in industrial parks are equipped with basic treatment facilities to recover useful raw materials, remove heavy metals, suspended solids (SS) and chemical oxygen demand (COD) to certain levels, and then discharge the

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treated wastewater to the unified WWTP set in industrial parks. The collected wastewater is subjected to primary, secondary and tertiary treatment before being discharged into surface water. The daily treatment capacity of a single WWTP ranges from 1,000 to 80,000 CMD, depending on the scale of an industrial park and its major industries (Industry Development Bureau 1994). For effective WWTPs, the effluents could become a relatively large and renewable resource, particularly during dry seasons. Chu *et al.* (2007) have assessed the potential of reused effluents discharged from several unified WWTPs of industrial parks in Taiwan, with designated capacity exceeding 10,000 CMD. The effluents generally have high totals of dissolved solids (TDS) and COD, while heavy metals and SS are not in significant concentrations since the wastewater was pretreated in the factories. The report indicated that the WWTP effluents possess recycling potential.

For further usage in industrial procedures, devices like RO should be applied to remove soluble salts and organics so that it meets most reusable water quality standards. Chen *et al.* (2005) adopted the process using high efficiency biological oxidation unit 'BioNET', sand filter, ultrafiltration and followed reverse osmosis to reclaim the WWTP effluents. The TDS and COD of the WWTP effluents were 3,000 and 50 mg/L. Their results demonstrated that the TDS and COD of the reclaimed water were 50 and 5 mg/L, respectively. It also confirmed the feasibility of applying membrane process to reclaim the wastewater from an industrial park WWTP. Based on previous work, this study utilizes a process similar to Chen *et al.* (2005) and uses a new RO pretreatment unit, the modified spiral wound membrane with backwash function, to reveal feasibility and corresponding performance. Treatment costs were also analysed at the end of this study.

METHODS

Backwashable spiral wound UF membrane

The fouling mechanism at the surface of the UF membrane is generally colloid clogging. Filtrate backwash is an effective way to displace the fouling layer and maintain membrane performance. For the elements of tubular and hollow-fibre configuration with asymmetric membrane structure, backwash is normally possible. For the spiral wound membrane, though the price for unit membrane area is relatively low, backwash is usually unavailable due to the possible risk of delamination. This restricts its use in wastewater reclamation. In this study, the conventional spiral wound module was modified to perform the backwash. Similar to the other commercial modules, it included the composite membrane (non-woven fabric supporting with PVDF coating, polyvinylidene difluoride) of cut-off molecular weight (MWCO) 50,000 ~ 100,000 Da, feed spacer, filtrate spacer (the tricot meshes), filtrate core tube and the housing made of FRP materials. In the modified module, a non-woven fabric of high mechanical strength was selected to manufacture the composite membrane. While conducting the reverse pressurizing tests on the flat-sheet membrane (attached with feed and filtrate spacers) using DI water, the delamination did not occur if the pressure was kept lower than 0.5 kg_f/cm^2, and the corresponding backwash flow rate was measured as 8 ~ 20 $L\,m^{-2}\,h^{-1}$.

In addition, feed spacers with parallelogram-shaped meshes were applied during the membrane manufacturing (Figure 1). In the trial stage, we compared the performance of UF modules using this spacer and another with square-shaped meshes. The results showed that the TMP elevation of the former was 20% lower, and less frequent chemical cleaning was required as well. One possible explanation is that the parallelogram-shaped meshes can induce more turbulence on the feed spacer and mitigate the colloid deposition. Further studies are required to reveal the mechanism.

THE PILOT PLANT

A pilot plant with the designed treating capacity of 1 m^3/h was installed in the unified WWTP of an industrial park in northern Taiwan. The process comprises three main components:

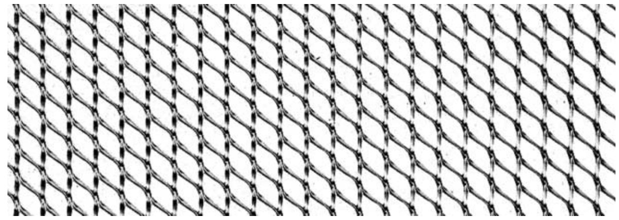

Figure 1 | The feed spacer with parallelogram-shaped meshes.

(1) Sand filter (Concord Technology, Taichung, Taiwan): The function SF is to remove the colloids over ten micrometres. The filter, filled with 280-litre quartz sands with a median size of 0.54 mm, has a diameter of 610 mm and height of 1,800 mm. The average pore size of the media was 16 μm as determined by mercury intrusion porosimetry.
(2) Backwashable spiral wound UF membrane (DF50-4040, Rum-Tech, Hsinchu, Taiwan): The function of UF is to remove the large molecules over 10^5 Da. The adopted configuration in the pilot plant was 40/40 (length 40 in. and diameter 4 in.) and the nominal membrane surface of one element was 6.3 m^2. Two UF elements were installed in parallel. DF50-4040 can sustain feedwater with pH levels from 2 to 13 as well as withstand exposure to chlorine. A 5-μm prefilter (PP filter) was installed upstream to prevent irreversible clogging of the spacer and membrane surface.
(3) RO membrane (FCS-4040HR, Rum-Tech, Taiwan): The function of RO is to remove TDS and soluble organics in the effluents. The configuration was spiral wound (40/40 configuration) with a nominal surface area of 6.75 m^2 for each element. The membrane was composed of composite polyamide (CA) and was neutrally charged. Two RO elements were installed in parallel. The module can sustain the feedwater with pH levels ranging from 2 to 13. A 1-μm prefilter is installed upstream in order to prevent irreversible clogging on the membrane surface.

The flow chart of the pilot plant is illustrated in Figure 2, and the designed/operating parameters of each component are listed in Table 1.

RESULTS AND DISCUSSION

Water quality of each stage

A piloting test was conducted from November 2005 to January 2006. Table 2 lists the quality of WWTP effluent and reclaimed water, as well as the suggested water quality of boiler feedwater at intermediate pressure (150 ~ 750 psig) by USEPA (USEPA 1992). Some items were not listed for

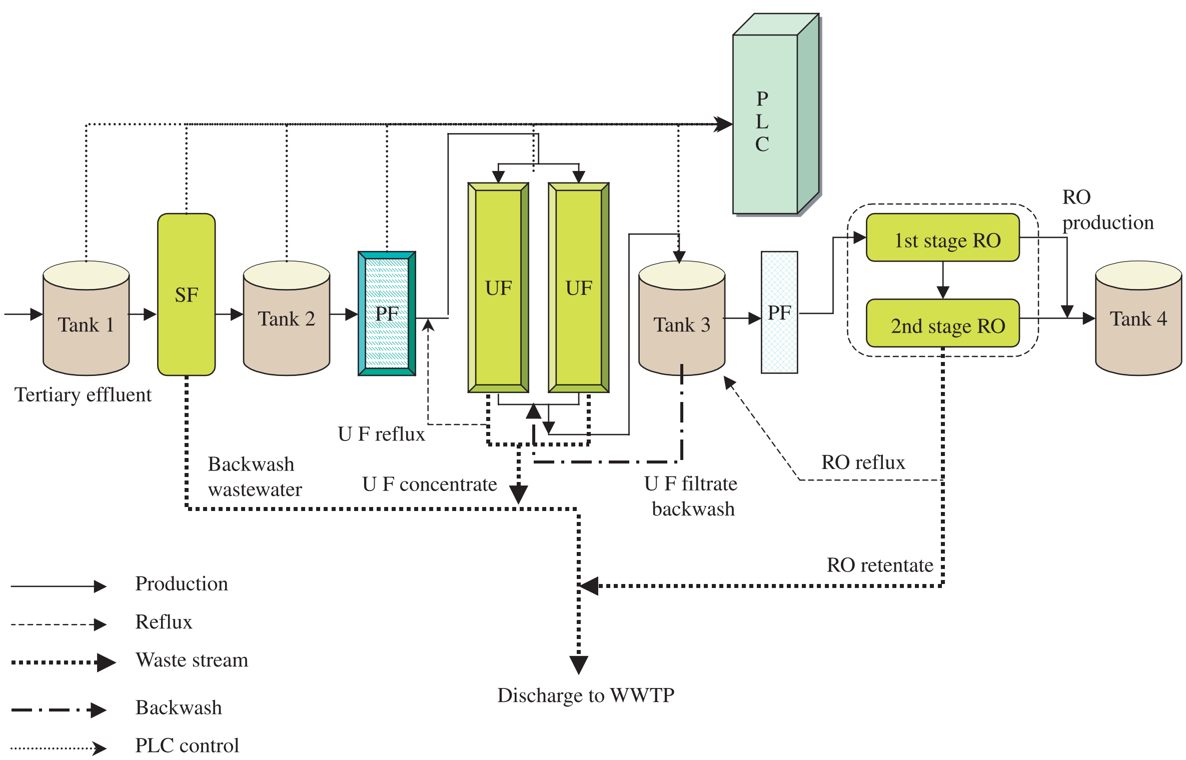

Figure 2 | The flow chart of the pilot plant.

Table 1 | The operating parameters of the pilot plant

	Protective device	Designed permeate rate ($m^3 m^{-2} h^{-1}$)	Recovery percentage (%)	Rinsing frequency (day^{-1})	Rinsing duration (min)	Rinsing flow rate ($m^3 m^{-2} h^{-1}$)	Addition of chemicals
SF	–	5	100	4	5 ~ 15	5*	5 ppm NaClO
UF	5-μm prefilter	0.08	65	96	3	0.008 ~ 0.02*	5 ppm NaClO
RO	1-μm prefilter	0.03	55	24	1	0.2	3 ppm anti-scalant + 3 ppm HCl + 3 ppm $NaHSO_3$

*Backwash.

sand filter and UF, owing to these units being unable to remove them, with examples including ammonia, nitrate and TDS. The selected WWTP performed well, and the tertiary effluent of the WWTP maintained stable quality throughout testing. The colour of the effluent, the only exception in this test, fluctuated markedly because the dye manufacturers in the complex manufactured different products, causing frequent change in wastewater composition.

UF could remove approximately 100% of the remaining SS, turbidity and *E. coli*. However, it was not able to remove soluble COD and colour-causing substances with molecular weight less than 10^4 Da. The SDI value (silt density index) of

Table 2 | The water quality of WWTP effluent and the reclaimed water

	Tertiary effluent	UF production	RO production	Boiler feed-water
pH	7.0 ± 0.2	7.1 ± 0.2	6.7 ± 0.2	8.2 ~ 10.0
SS (mg/L)	13 ± 3	0.4 ± 0.1	ND	5
COD (mg/L)	28 ± 4	16 ± 2	3 ± 1	5
Colour (–)	50 ± 20	40 ± 20	<5	–
E. coli (CFU/100 mL)	$10^3 \pm 10^1$	ND	ND	–
NO_3–N (mg/L)	22 ± 1	*	0.3 ± 0.1	–
NH_3–N (mg/L)	1.2 ± 0.1	*	0.2 ± 0.1	0.1
Turbidity (NTU)	5.2 ± 0.9	0.2 ± 0.05	0.1 ± 0.02	–
TDS (mg/L)	1,700 ± 120	*	45 ± 15	500
Hardness (mg/L as $CaCO_3$)	430 ± 110	*	9 ± 3	1.0
Alkalinity (mg/L as $CaCO_3$)	290 ± 30	*	33 ± 5	100
Silica (mg/L as SiO_2)	20 ± 3	*	0.4 ± 0.3	10
Ca (mg/L)	48 ± 5	*	0.1 ± 0.1	0.4
Mg (mg/L)	74 ± 12	*	0.2 ± 0.1	0.25

UF filtrate, however, was consistently lower than 4 and suitable for RO influent. Following treatment with RO, over 98% of TDS, hardness substances, and silica were removed. The removal percentage of COD also exceeded 95%. Nevertheless, the pH levels of RO permeate were reduced to a mild acid state due to the addition of hydrochloric acid to prevent scaling. The adjustment of pH levels would be required if used for the boiler feedwater. Additionally the hardness (9 mg/L) also slightly exceeded the required value (1 mg/L). A polish ion exchange resin may help reduce the hardness and TDS.

LONG TERM OPERATION

In recycling the WWTP effluents using the aforementioned membrane process, the UF module probably is the most crucial unit. It not only removes all micro-scale and nano-scale colloids which cannot be intercepted upstream (probably in concentration of 10^2 mg/L), but also provides qualified influent for consistent RO performance (SDI < 5, say). A suitable operating strategy may help elevate system performance and reduce cost, especially the replacement of expensive membrane elements. This section focuses on the performance of the modified UF module, DF50-4040. Figures 3 and 4 depict the results of permeate flux and TMP variation during the piloting test. The recovery percentage of UF was set at 60%, while the operating cycle included the following stages: 10 minutes for filtration, 3 minutes for backwash (with 10 ppm NaClO addition) and 1 minute for keeping still. The purpose of keeping still is to allow the UF membrane structures to revert to original status after the reverse pressurization of backwash. During the tests, the turbidity after the 5-μm prefilter constantly ranged from 0.8 to 1.0 NTU and was suitable for UF influent. Figure 3 demonstrates that the membrane flux ranged around 0.06 ~ 0.07 $m^3 m^{-2} h^{-1}$ (81 ~ 87% of the designed value). For every month or for the flow rate decreasing to 70% of its designed value, the chemical cleaning of the UF membrane was performed. After cleaning, the flux significantly increased. For the TMP results (Figure 4), it ranged from 0.8 to 1.0 kg_f/cm^2 and showed no significant change after chemical cleaning. Restated, the backwashable UF module performed consistently during the tests.

In practical operations, the backwash was performed every 10 minutes and each rinse took 3 minutes. The preceding reverse pressurization test demonstrated that backwash pressure should not exceed 0.5 kg_f/cm^2. Thus the backwash was performed at pressure 0.3 kg_f/cm^2, avoiding the occurrence of delamination after long-time operation. The backwash flux was measured as 0.015 $m^3 m^{-2} h^{-1}$. Due to this circumstance, the required filtrate for backwash accounts for 9 ~ 10% of the filtrate. The turbidity of backwash streams ranged from 1.5 to 4.0 NTU, implying that significant amounts of colloids accumulating in the membrane modules could be expelled during the backwash. Comparing with other backwashable spiral wound membrane, *Reverse Spiral* (Hydranautics), a low-pressure membrane used for the RO pretreatment of seawater desalination, its backwash pressure is designated as 1.7 kg_f/cm^2 and the flux at 0.065 ~ 0.125 $m^3 m^{-2} h^{-1}$ (accord-

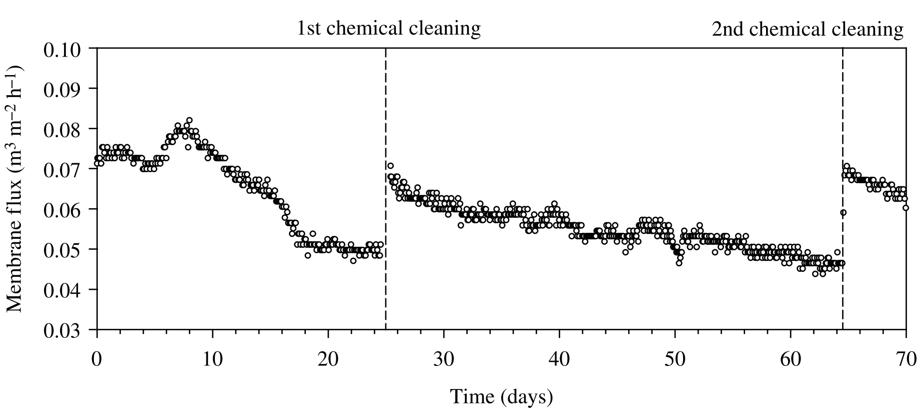

Figure 3 | The temporal variation of UF membrane flux.

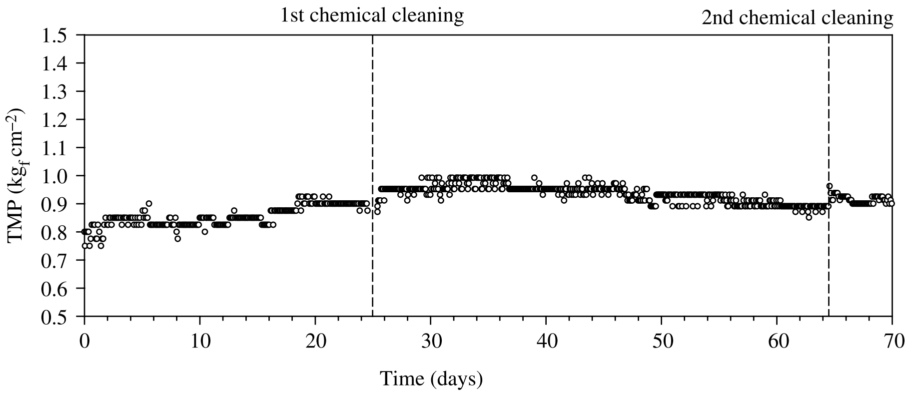

Figure 4 | The temporal variation of UF membrane TMP.

ing to the product data sheet). The membrane is backwashed every 30 minutes for 30 seconds and thus the required backwash flow consumes approximately 5% of the UF filtrate. The backwash of DF50-4040 apparently operates under lower pressure, lower flux, more frequent backwash and more filtrate consumed. More investigation is required to improve the module to improve production efficiency.

Other maintenance procedures of the backwashable UF module included:

1. The 5-μm prefilter was replaced every two weeks to keep pressure drop constantly lower than 1 kg_f/cm^2, also preventing the risk of colloid breakthrough and entering the UF membrane. During the trial stage, it showed that the 10-μm and 25-μm filters has a longer lifetime (replaced every one month) but the filter turbidity could not be kept under 1 NTU but ranged from 1.5 to 2.2 NTU. This was not considered in the criterion for the influent of spiral wound UF module.
2. For chemical cleaning of UF membrane, the operator closed the valves of the filtrate end and concentrate end, and loaded 20 L of patented cleaning chemicals (RCB-15, mainly containing polyphosphate anti-scaling reagents, anionic surfactants, sodium hydroxide and disinfectants; pH 12) along with 80 L of tap water. The chemicals were circulated in the membrane modules for 20 minutes, kept still for 10 minutes, and circulated with tap water. The pH levels of the flushing stream were measured on line and recirculation stopped when the pH level reached 7.5.

Compared with independent tests using a hollow fibre membrane of polyester sulfone (Chu *et al.* 2007), the spiral wound UF had a more stringent requirement on the influent turbidity (lower than 1 NTU), while the hollow fibre UF could tolerate up to 2 ~ 4 NTU. Also the current recovery ratio 60% was lower than the hollow fibre membrane (usually 80%). Further improvement on the spiral wound membrane is required in order to be applied in wastewater reclamation.

During the piloting tests, RO had a stable performance. The removal percentage of TDS stably maintains at 97 ~ 98% (Figure 5), which gave the production of TDS around 40 ~ 60 mg/L. This removal efficiency is slightly lower than the general RO performance (around 99% to 99.5%). The possible reason could be raised from high salinity (TDS nearly 2,000 mg/L and conductivity nearly 4 mS/cm) and high organic content (COD nearly 30 mg/L) in the industrial wastewater, and this somehow deteriorated the RO performance on the TDS removal efficiency. On the other hand, the RO permeate flux was around 0.035 ~ 0.039 $m^3 m^{-2} h^{-1}$ (Figure 6), and the flow rate reached 0.5 m^3/h (12 m^3/day), approximately 15% higher than the designed value of RO. A higher inlet pressure was applied (6 ~ 6.5 kg_f/cm^2) for achieving higher flow rate, while the suggested value is 5 ~ 5.5 kg_f/cm^2. The chemical cleaning of the RO membrane was applied every two months, according to the manufacturer's suggestion.

Cost estimation

Cost estimation was conducted according to the pilot plant results. Considering that scaling up a full-scale plant for

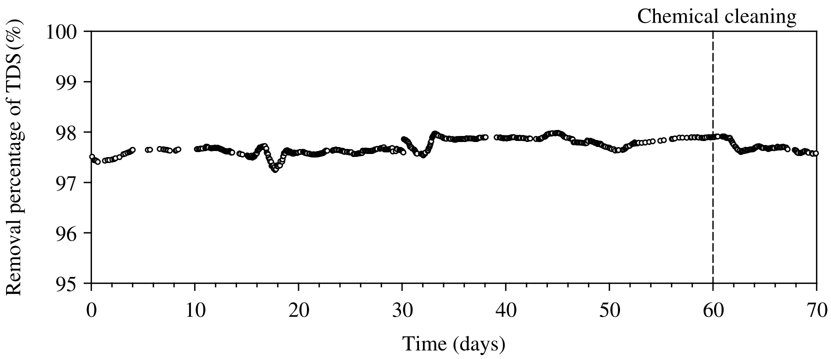

Figure 5 | Salt removal efficiency of RO.

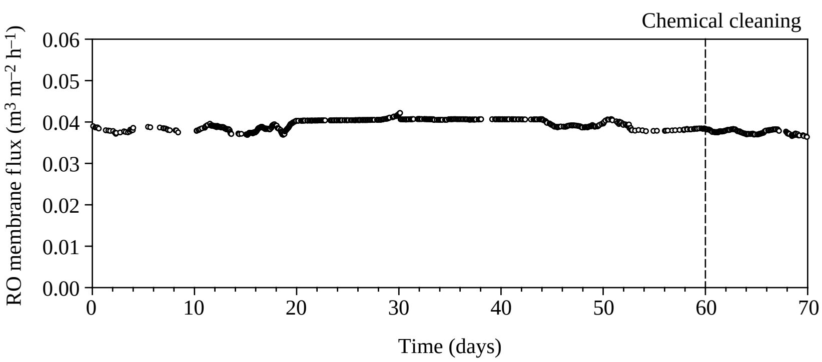

Figure 6 | Flow rate variation of RO.

producing RO permeate of 5,000 m^3/day, the total cost (including the construction and routine operation/maintenance) is summarized in Table 3. The principles of cost estimation followed the 'Budgeting Rules' regulated by Public Construction Commission, Taiwan (PCC). The construction costs in this table include land levelling, storage tank, sand filter, UF, RO, devices for monitoring and controlling, piping and electricity distribution system. Routine O&M include the consumables (UF and RO membranes, filter sands, prefilters and chemicals), personnel salary and insurance fee. For one cubic metre of RO permeate, the construction cost was US$ 0.35 and O&M cost was US$ 0.45. Compared with other independent tests using hollow fibre membrane as an alternative (Chu *et al.* 2007), using backwashable spiral wound UF could achieve a 9% reduction of total cost. This may be due to the lower price for the spiral wound UF (approximately US$ 120/m^2) relative to the hollow fibre membrane (approximately US$ 160/m^2).

Though technically feasible, promoting the reclamation of wastewater using the membrane system in industrial parks is still difficult due to low water tariffs in Taiwan (approximately US$ 0.3/m^3). The other difficulty is the lack of confidence in the stability of water quality, even though RO permeate exhibits much better quality than tap water. In order to further promote wastewater reclamation, longer operating pilot plants are required, as well as continuing to modify backwashable spiral membranes for further cost reduction.

CONCLUSIONS

In this study, the membrane process was utilized to reclaim the effluent from the unified WWTP of an industrial park in northern Taiwan. The process comprised the sand filter, backwashable ultrafiltration and reverse osmosis. The design of ultrafiltration was modified to perform backwash at 0.3 kg_f/cm^2 and of flux 0.015 $m^3\,m^{-2}\,h^{-1}$. The evaluating results showed that the pilot plant performed consistently

Table 3 | Cost estimation of full-scale plant for producing 5,000 m^3/day RO permeate

Process Items	SF + Hollow-fibre UF + RO	SF + Spiral-wound UF + RO
Construction cost (US$)	6,200,000	5,600,000
Construction cost (US$/m^3 production)		
Land levelling	0.02	0.02
Piping works	0.03	0.03
Sand filter	0.02	0.03
Ultrafiltration	0.14	0.09
Reverse osmosis	0.09	0.07
Chemical dosing system	0.00	0.00
Electricity system	0.03	0.03
Control and monitoring	0.03	0.03
Miscellaneous	0.05	0.05
Summary	0.41	0.35
O&M cost (US$/m^3 production)		
Electricity charge	0.08	0.10
Membrane replacement	0.23	0.17
Chemicals and other consumables	0.09	0.11
Maintenance	0.03	0.02
Personnel and insurance	0.04	0.05
Summary	0.47	0.45
Total cost (US$/m^3 production)	0.88	0.80

Note: The costs listed in the table 3 are only for reference and may vary due to currency, price index, discount provided by manufacturers, and actual planning.

during the two-month operation. The backwashable UF could produce filtrate of SDI below four and be suitable for RO influent. After the RO desalination, the water quality of the reclaimed water basically met the feed water quality requirement of intermediate-pressure boiler (150 ~ 750 psig) of the Environmental Protection Agency, United States (USEPA), though the hardness is slightly higher. The backwashable spiral wound UF membrane provided suitable water quality for RO influent and helped reduce costs compared to using hollow-fibre UF membrane. The total cost of recycling one-ton effluent included US$ 0.35 for construction and US$ 0.45 for operation/maintenance. Using the backwashable UF module could help save 9% total cost in contrast to using the hollow-fibre UF membrane.

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