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Fouling inhibition of RO membrane separation by two-stage H_2O_2/UV pre-oxidation for municipal wastewater reuse

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ABSTRACT

This study evaluated the performance of combining two-stage H_2O_2/UV pre-oxidation with RO post-separation for the reuse of municipal wastewater. The results demonstrated that the two-stage H_2O_2/UV (H_2O_2 = 0–30 mg/L) process was more effective than the one-stage (H_2O_2 = 0–60 mg/L) process for mitigating RO membrane organic-fouling and bio-fouling. In thetwo-stage operation, the inactivated log reduction of microorganisms reached 4.96-logs, and the total organic carbon (TOC) was reduced from 18.0 to 2.98 mg/L. The silt density index (SDI) decreased from 9.8 to 3.9; the normalized flux decline (*r*) of RO separation was enhanced from 36% to 91%.

Keywords: Membrane; Fouling; H_2O_2/UV; Municipal wastewater; Reuse

1. Introduction

At present, biological wastewater treatment is currently the most widely used method for removing organic pollutants from municipal wastewater. However, the biological treatment always requires a larger construction area and requires a longer treatment time than the advanced oxidation processes (AOPs). In addition, the disposal of excess biomass is a significant cost factor [1]. Thus, de Koning et al. suggested the direct membrane filtration of wastewater as well as advanced oxidation processes (AOPs) [2]. These two processes are becoming increasingly more important because harmful substances, such as pesticides and endocrine disrupters, are given priority in the municipal wastewater.

H_2O_2/UV is a type of AOP that is less pH-dependent and generates no chemical sludge. H_2O_2/UV generally functions in the presence of hydroxyl radicals (HO·) through direct photolysis of H_2O_2 under UV irradiation, as is shown by Eq. (1). This process is very effective in removing resistant, toxic, and poorly biodegradable pollutants from wastewater due to the presence of HO· [3–7]. This method is not only very effective for removing organic pollutants but also for simultaneous disinfection [3,8].

$$H_2O_2 \xrightarrow{hv} 2\,HO\cdot \quad (1)$$

Alternatively, membrane technologies have proven to be effective for removing most of the organic and inorganic compounds and microorganisms from water and have been widely applied to wastewater reclamation [9]. However, fouling inhibition and control are the main challenges as they severely affect the operating costs as fouling drastically reduces the permeate flux and can cause membrane failure in extreme situations [10–14]. Therefore, the pretreatment of the feedstock has been proposed as a key task to fouling inhibition [15–21]. Thus,some researchers integrated H_2O_2/UV with reverse osmosis (RO) to treat textile wastewater for reuse [22], H_2O_2/UV with NF membranes to treat natural organic matter [23], and ozone with MF membrane to reuse secondary effluent [24].

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The water resources of Taiwan mainly derive from precipitation during the rainy seasons and typhoons; however, these severe weather events are often less predictable. Hence, the reuse of municipal wastewater is a viable alternative for meeting the country's increasing water demands due to rapid industrialization. Currently, the amount of municipal wastewater is approximately 4,600,000 CMD (m^3/day) in Taiwan [25]. Thus, the main objective of this study is to evaluate the performance of combining H_2O_2/UV pre-oxidation with RO post-separation for the reuse of municipal wastewater with emphasis on membrane fouling inhibition. Moreover, we attempt to investigate the treatment efficiency of one-stage and two-stage H_2O_2/UV processes. The evaluated water parameters include the disinfection of total coliform, the silt density index (SDI), the molecular weight (MW) distribution, and the flux decline of the RO membrane.

2. Material and methods

2.1. Municipal wastewater

Municipal wastewater was sampled from a community wastewater treatment plant located in Kaohsiung City, Taiwan. The wastewater contained approximately 450–500 CMD; the details of the composition of raw wastewater and discharged wastewater are listed in Table 1. The raw wastewater was treated sequentially by screens, pH adjustment, biological contact aeration, and rapid gravity filtering before discharge. The discharged wastewater was sampled for further H_2O_2/UV oxidation and RO membrane separation for multifunction reuse, such as landscape irrigation, toilet flushing, and drinking water. The sampled discharged wastewater had a pH of 7.3, biochemical oxygen demand (BOD) of 21 mg/L, chemical oxygen demand (COD) of 57 mg/L, total organic carbon (TOC) of 18 mg/L, color of 47 ADMI (American Dye Manufacturers Institute) units, suspended solids (SS) of 23 mg/L, and total coliform of 420,000 CFU/100 mL.

2.2. Pilot-scale H_2O_2/UV treatment combined with membrane separation

The process of the present wastewater treatment is shown in Fig. 1a and the corresponding pilot diagram is portrayed in Fig. 1b. The influent (i.e., the sampled discharged wastewater) was filtrated by a 5-μm filter (KEMFLO, PS-05) and 1-μm filter (KEMFLO, PS-01) in sequence first. Next, the wastewater was treated by ultraviolet lights by flowing through the 1st and 2nd cylindrical quartz chambers containing UV lamps (Light Sources GPH 436T5L). The UV lamp was a low pressure mercury vapor type that emitted energies of 7.3 W per lamp,mostly at wavelengths of 254 nm with a flux of 72 μW/cm². Before the UV light treatment, a fixed amount of H_2O_2 (35% w/w, Chang-Chun Petrochemical Co., Ltd.) was added into the wastewater. The wastewater retention time for each UV lamp was 300 s. After oxidization by H_2O_2/UV, the wastewater was further separated by an RO membrane (TFC membrane, Rotek Water System Co. LTD). The wastewater quality was analyzed by sampling at appropriate sampling ports in the treatment process shown in Fig. 1a. All the experiments were conducted at room temperature.

Table 1
Municipal wastewater composition

	Raw wastewater	Discharged wastewater
pH	7.1	7.3
BOD (mg/L)	115	21
COD (mg/L)	208	57
TOC (mg/L)	51	18
SS (mg/L)	207	23
Turbidity (NTU)	–	125
Total coliform (CFU/100 mL)	–	420,000
Color (ADMI)	125	47

2.3. Wastewater treatment efficiency

2.3.1. Disinfection efficiency

The survival ratio of microorganisms is commonly expressed as an inactivation ratio (in %) or as the number of reductions in order of magnitude of the microorganism concentration. In this study, we adopted the log reduction as the disinfection efficiency, as given by Eq. (2):

$$\log \text{reduction} = \log_{10}\left(\frac{N_0}{N_t}\right) \tag{2}$$

where N_0 and N_t denote the number of microorganisms before and after treatment, respectively.

2.3.2. H_2O_2/UV oxidation

The wastewater treatment efficiency by H_2O_2/UV was calculated by Eq. (3):

$$\text{Removal}\ (\%) = \left(\frac{C_i - C_e}{C_i}\right) \times 100 \tag{3}$$

where C_i and C_e are the concentrations of the influent and effluent of various water quality parameters, respectively.

2.3.3. RO separation

The rejection efficiency of RO membrane separation was calculated by Eq. (4):

$$\text{Rejection}\ (\%) = \left(1 - \frac{C_p}{C_f}\right) \times 100 \tag{4}$$

Where C_p and C_f represent the concentrations of the permeate and feed water, respectively. During filtration, the permeate flux, (L/m²·h), was measured using a scaled volumetric cylinder at an interval of 1 h and was calculated by Eq. (5):

$$J_t = \frac{V_t}{A \cdot t} \tag{5}$$

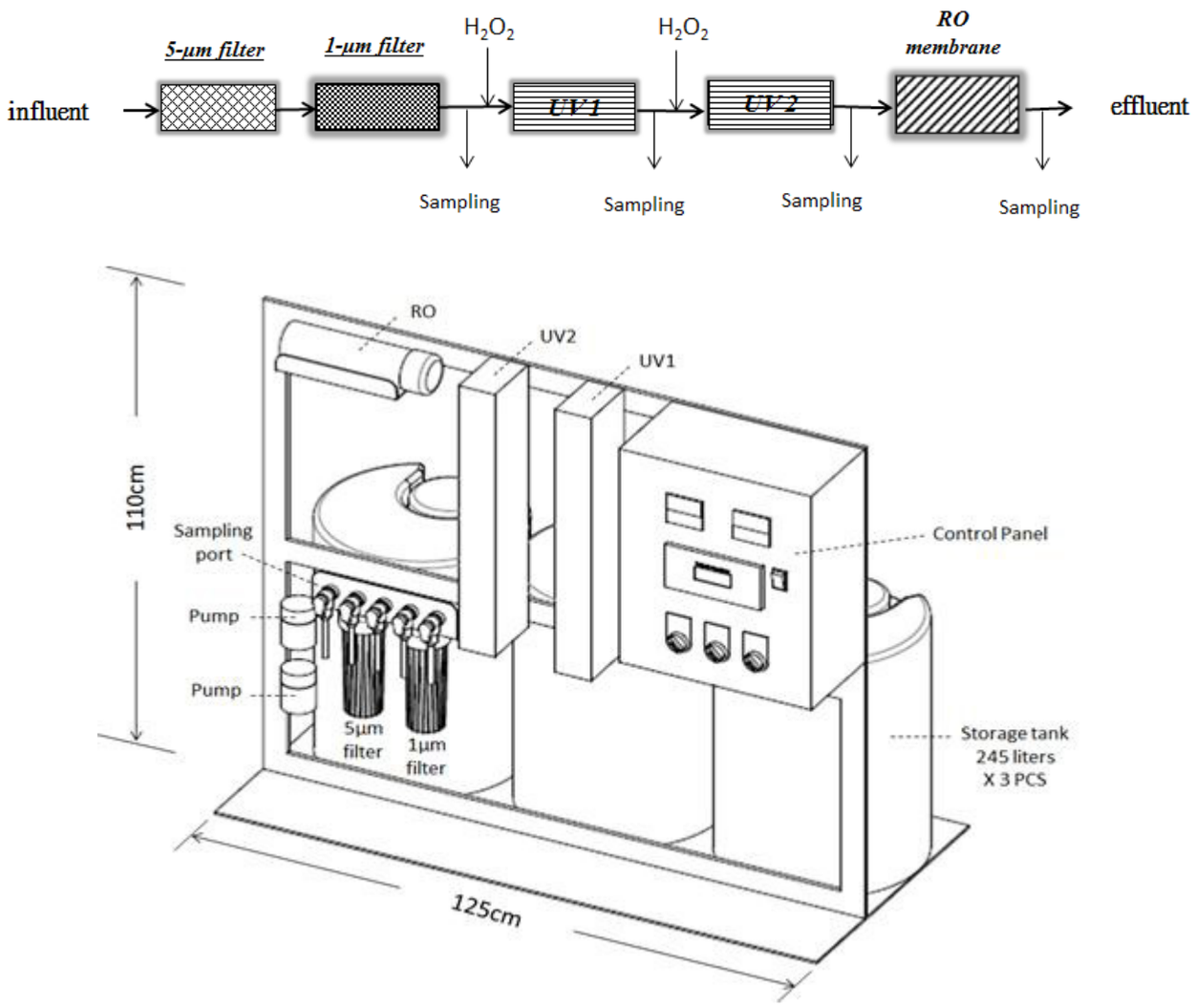

Fig. 1. (a) Wastewater treatment process. (b) The pilot diagram corresponding to Fig. 1a.

where is the permeate volume (L) at time t (h), and A is the membrane surface area (m^2). The normalized flux decline r was calculated according to Eq. (6):

$$r(\%) = \frac{J_t}{J_1} \times 100\% \tag{6}$$

where the subscripts 1 and t denote the time of filtration at the first hour and the t-th hour, respectively. Furthermore, for efficient and economic operation, the SDI of the feed water to the RO membrane needs to be equal to or less than 5. The SDI was calculated by Eq. (7) [26]:

$$\text{SDI} = \left(1 - \frac{t_i}{t_f}\right)\frac{100\%}{t_T} = \frac{\%P}{t_f} \tag{7}$$

where t_i is the time interval of collecting the initial 500 ml of permeate, t_T is the elapsed time (15 min), and t_f is the time interval of collecting 500 ml of permeate after t_T. If the plugging ratio (%P) exceeds 75%, a shorter period t_T is required, e.g., 10, 5 or 2 min.

2.4. Chemical analysis

The pH, COD, BOD, TOC, color, SS, and total coliform were measured according to the procedures of the Standard Methods [27]. The total organic carbon analyzer (Model 700; O.I. Corporation) was used to determine TOC. The color measurement was based on the ADMI tristimulus filter method by scanning light from 400 to 700 nm using a UV-VIS spectrophotometer (Hitachi U-2001) coupled with a computer for data calculation. Additionally, total coliform was enumerated by the membrane filter method using M-Endo agar (Merck, German). Plates (duplicate) were incubated at 35°C for 24 h; the pink to dark-red colonies with metallic surface sheen were then counted as the total coliform.

The organic MW distribution was determined by ultrafiltration through hollow fiber membranes with MW cutoffs

of 100 kDa, 10 kDa, and 1 kDa (A/G Technology Corporation). The pressure applied during the filtration was 20 psi. This study regarded the MW range of 0.45 μm – 100 kDa, 100 K – 10 kDa, 10 K – 1 kDa, and below 1kDa as high, medium, low, and extra low MW fractions, respectively. Prior to the color and MW distribution measurements, the samples were filtered through a 0.45 μm filter (ADVANTEC®, Japan). The SDI was examined according to the ASTM method D-4189-07 (Simple SDI, Procam Controls Inc.).

3. Results and discussion

3.1. Performance H_2O_2/UV oxidation on disinfection

The disinfection efficiency of the H_2O_2/UV process on total coliform is shown in Fig. 2 for the processes of UV1, UV2, and combined UV1 with UV2 (denoted by UV1 + UV2) with H_2O_2 doses ranging from 0 to 60 mg/L. The inactivated total coliform log reduction was calculated from Eq. (2). Fig. 2 shows that for UV1, the inactivated total coliform increased as the H_2O_2 dose increased. However, for UV2, the disinfection efficiency increased as the H_2O_2 dose increased from 0 to 30 mg/L, and remained nearly constant as the H_2O_2 dose increased further to 60 mg/L. This is because the total coliform concentration was higher before UV1 treatment. After UV1 treatment, the concentration of total coliform was reduced. Thus, most microbes were inactivated at the UV1 stage. Furthermore, without adding H_2O_2 the inactivated log reduction was lower than 1 irrespective of using UV1, UV2, or UV1 + UV2. That is, it is difficult to reach the disinfection goal by using UV alone unless either the disinfection time was extended or the H_2O_2 dose was added. Moreover, the inactivated log reduction of UV1 + UV2 was 1.6–1.8 times that of UV1 alone for the same H_2O_2 concentration from 10–60 mg/L as illustrated in Fig. 2. It indicated that the added UV2 lamp could enhance the disinfection of total coliformindeed.

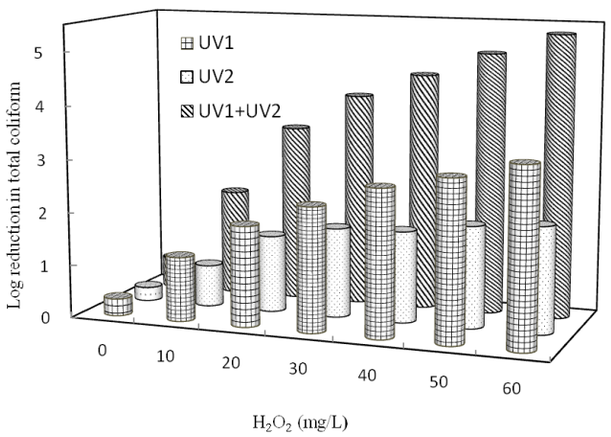

Fig. 2. Disinfection performance of the H_2O_2/UV process.

To examine the merits of the treatment processes, the water quality standard of total coliform converted to the disinfection efficiency of log reduction is shown in Table 2. The total coliform of the original effluent was 420,000 CFU/100 mL. For the treated water to comply with the effluent standard of 200,000 CFU/100 mL, the log reduction has to be larger than 0.32, which could be achieved using UV1 alone. For satisfying the drinking water resource standard, i.e., total coliform <20,000 CFU/100 mL, the log reduction has to be higher than 1.32, which could be readily achieved by the process of either UV1 (H_2O_2 = 20 mg/L) or UV1 + UV2 (10 mg/L). To meet the land irrigation and toilet flushing standards, i.e., total coliform <200 CFU/100 mL (i.e., greater than 3.32-logs), the minimum requirement was either UV1 (H_2O_2 = 60 mg/L) or UV1 + UV2 (H_2O_2 = 20 mg/L). In contrast, only the two-stage process of UV1 + UV2 with H_2O_2 (50 mg/L, minimum) could conform the drinking water standard of 6 CFU/100 ml (i.e., greater than 4.85-logs). That is, the two-stage H_2O_2/UV disinfection process is very efficient for treating the municipal wastewater for reuse.

According to the research of Yasar et al. [28], the disinfection mechanism of AOPs was based on the cell wall weakening by the HO· attacks, which allowed H_2O_2 to diffuse into the bacteria, and led to the irreversible bacterial damage (i.e., no regrowth) without requiring any additional chemicals. Thus, by summarizing the literature results with ours in Table 3, it is evident that the disinfection efficiencies by the H_2O_2/UV process for different water samples were all larger than 3 log reduction, irrespective of variations in the UV and H_2O_2 dose. For comparison, Yasar et al. using a UV flux of 5 mW/cm² combined with 170 mg/L H_2O_2 and an irradiation time of 170 s, obtained a total coliform reduction of 3.0-logs [28]. Our two-stage UV1 + UV2 (H_2O_2 = 30 mg/L) process with a light flux of 72 μW/cm² per lamp led to a total coliform reduction of 4.96-logs. In addition, the H_2O_2/UV process is also an effective disinfection method

Table 2
Micro organism log reduction of H_2O_2/UV disinfection

Standard	CFU/100 mL	Minimum log reduction	Minimum requirement		
			UV	H_2O_2 (mg/L)	Treated log reduction
Effluent	<200,000	>0.32	UV1	0	0.32
Drinking water resource	<20,000	>1.32	UV1	20	1.89
			UV1 + UV2	10	2.00
Land irrigation and toilet flushing	<200	>3.32	UV1	60	3.32
			UV1 + UV2	20	3.40
Drinking water	<6	>4.85	UV1 + UV2	50	4.96

Table 3
Comparison of disinfection efficiency of the H_2O_2/UV processes

Water sample	Microbe	UV intensity/flux	UV intensity/flux (mWs/cm²)	H_2O_2 (mg/L)		Reduction (logs)	Reference
Municipal secondary effluent	Total coliform	5 mW/cm² 60 s	300	170		3.0	[28]
Humic surface water	Total coliform	681 (mW s/cm²)	681	0.125		3.6	[29]
				3.0		6.2	
Humic surface water	*E. coli*	40 μW/cm² 90 s	3.6	50		4.0	[30]
Municipal secondary effluent	Total coliform	72 μW/cm² (300 s)	21.6	UV1	60	3.32	This study
				UV1 + UV2	20	3.40	
				UV1 + UV2	30	4.96	

for total coliform and E. coli in humic surface waters[29, 30]. In other words, the H_2O_2/UV process is useful for water and wastewater disinfection.

3.2. Water quality improvement by H_2O_2/UV pre-oxidation

3.2.1. SDI trends

The SDI is an empirical parameter used to characterize the fouling potential of the RO membrane of a feed water stream. Fig. 3 shows the results of the SDI obtained from Eq. (7). The SDI of the wastewater after pre-filtration by the 1-μm filter was 9.8. After H_2O_2/UV oxidation, the SDI decreased to 7.4, 4.7, and 3.9 using UV1 (H_2O_2 = 60 mg/L), UV1 + UV2 (H_2O_2 = 20 mg/L), and UV1 + UV2 (H_2O_2 = 30 mg/L), respectively. Although it is generally suggested [31] that the SDI of the water fed to an RO membrane is 5.0 to avoid fouling, only the two-stage operation condition of UV1 + UV2 (H_2O_2 = 20 mg/L) and UV1 + UV2 (H_2O_2 = 30 mg/L) comply with this criteria.

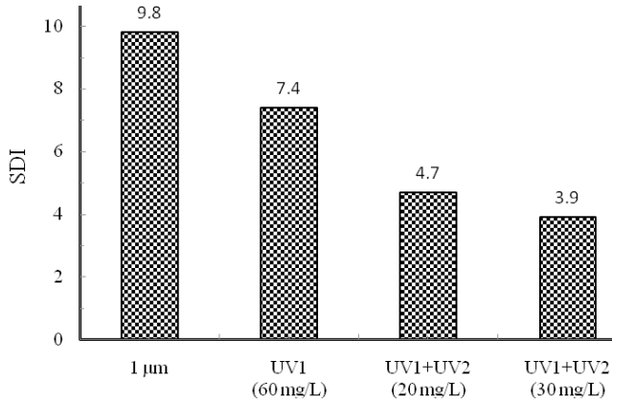

Fig. 3. Effect of H_2O_2/UV pre-oxidation on SDI value.

3.2.2. MW distribution

The H_2O_2/UV oxidation is widely recognized as a good water reclamation treatment technique. The oxidation process, in which the organic matter is broken down into compounds of smaller MW or mineralized to CO_2 and H_2O, affects the characteristics of the treated effluent [6,32]. Fig. 4 shows the MW distributions before and after the process of H_2O_2/UV oxidation. It reveals that the TOCs of the high, medium, low, and extra low MWs of the wastewater treated by the 1-μm filter were 7.8, 6.7, 2.4, and 1.1 mg/L, respectively. This indicates that most of the organics were in the ranges of high and medium MWs. In contrast, there was only a very small amount of TOC of MW lower than 10 kDa. However, after UV1 (H_2O_2 = 60 mg/L) oxidation, as shown in Fig. 4, the TOCs of the high, medium, low, and extra low MWs were 1.23, 2.35, 1.69, and 1.52 mg/L, respectively. The phenomena indicated that in the oxidation process, the contents of high and medium organics were dramatically reduced,whereas that of MW < 1 kDa increased slightly due to the breakdown of the organic matter, as described previously. In addition, after the two-stage H_2O_2/UV process, the TOCs of the four MWs were all decreased for both UV1 + UV2 (H_2O_2 = 20 mg/L) and UV1 + UV2 (H_2O_2 = 30 mg/L)

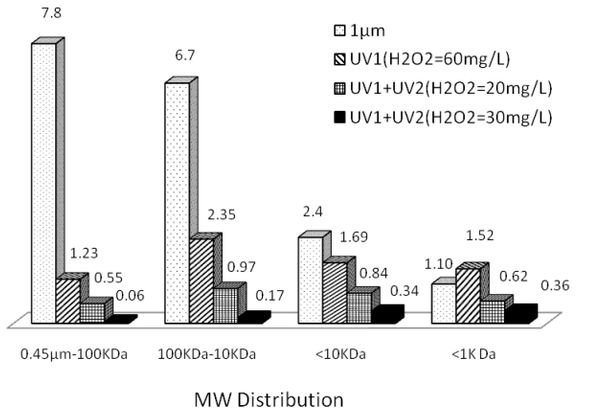

Fig. 4. Comparison of MW distributions with H_2O_2/UV oxidation.

treatment. In the latter case, the TOCs were almost completely mineralized, except those of low and extra low MW organics still had residues of 0.34 and 0.36 mg/L, respectively. Eq. (1) shows that more H_2O_2 concentration will lead to more HO· so that the oxidation of organics could be improved. Further, the reason for the improvement of UV1 + UV2 over UV1 alone was that the added UV2 played the

role of further treating those residuals not treated by UV1, including both disinfection and oxidation.

3.2.3. Performance of H_2O_2/UV pre-oxidation combined with RO post-separation

The results described above show that the H_2O_2/UV pre-oxidation effectively mineralized TOC. Thus, the permeate flux of the RO membrane was examined using four tests denoted by RO1, RO2, RO3 and RO4, respectively. RO1, RO2, RO3 and RO4 refer to wastewater treated by the 1 μm filter without H_2O_2/UV pre-treatment, by UV1 (H_2O_2 = 60 mg/L), by UV1 + UV2 (H_2O_2 = 20 mg/L), and by UV1 + UV2 (H_2O_2 = 30 mg/L), respectively. The permeate flux and normalized flux decline (*r*) are shown in Fig. 5a and 5b, respectively. They reveal that the permeate flux of RO1 was 43.1 L/m²·h after filtration for 1 h (*r* being 100%) and rapidly declined to 28.4 L/m²·h after filtration for 10 h (r being 66%), and then declined to 11.2 L/m²·h after filtration for 30 h (*r* being 36%). That is, by filtration for 30 h, most of the pores were blocked. Although the RO separation could effectively remove the TOC, the serious fouling problem was not desirable. For RO2, the permeate flux was 55.1 L/m²·h after the first hour; the obviously declined flux induced a gradual reduction of *r* to 55% after filtration for 30 h. In contrast, for RO3 and RO4, the permeates were respectively 56.9 and 58.1 L/m²·h after the first hour, and remained at 41.7 and 52.6 L/m²·h after filtration for 30 h, with corresponding *r* values of 73% and 91%. That is, the two-stage H_2O_2/UV pre-oxidation process effectively inhibited fouling caused by the organic matter and significantly mitigated the permeate flux decline. In particular, the condition of UV1 + UV2 (H_2O_2 = 30 mg/L) mitigated the permeate flux decline obviously and increased the *r* value from 36% to 91%.

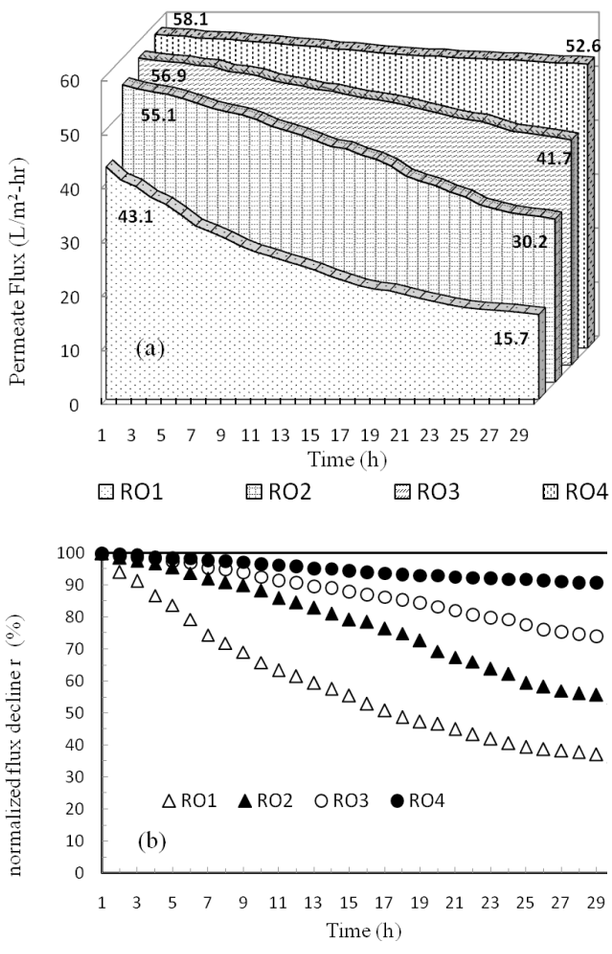

Fig. 5. (a) The permeate flux and (b) normalized flux decline (r).

For further illustration, we defined the percentage of the average flux decline per liter permeate (η_d) (%/m²·L) by Eq. (8). The results listed in Table 4 show that for RO1, η_d was 0.084%/m²·L; i.e., by collecting 1 L of permeate, the average flux decline was 0.084%/m²·L. For RO2, η_d was 0.035%/m²·L, revealing that even the one-stage H_2O_2/UV pro-oxidation process could effectively improve the flux decline. For the two-stage H_2O_2/UV pre-oxidation processes of RO3 and RO4, the corresponding η_d values were only 0.018 and 0.005%/m²·L, indicating that H_2O_2/UV pre-oxidation efficiently extended the operation life of the RO membrane (especially RO4).

$$\eta_d = \frac{\sum_0^t J_t}{t} \tag{8}$$

where J_t (L/m²·h) was measured by a scaled volumetric cylinder at an interval of 1 h, *t* is the operation time, and the total operation time was 30 h.

As a comparison, Table 5 tabulates various AOPs combined with membranes from the literature for fouling inhibition. The pre-oxidation processes included the photocatalytic oxidation, H_2O_2/UV, O_3/H_2O_2, and the Fenton process. Wastewater is found in such forms as the following: dye wastewater, landfill leachate, olive mill wastewater, drinking water resources, and ground water. All of these pre-oxidation processes of AOPs exhibited significant fouling mitigation. Thus, AOP is an effective pre-treatment process for fouling inhibition of membrane separation.

3.4 Comparison of water quality ofdifferent treatment processes

For further elaboration, the water qualities of different wastewater treatment processes and the associated standards are tabulated in Table 6. The results show that the total coliform of the wastewater treated by the 1 μm filter was 380,000 CFU/100 mL, which still did not meet the Taiwanese effluent standard of 200,000 CFU/100 mL. How-

Table 4
η_d of the four operation processes

Operation processes	Flux decline after 30 h (%)	Permeate produced (L/m²)	η_d (%/m²·L)
RO1	64	758.3	0.084
RO2	45	1284.3	0.035
RO3	27	1490.4	0.018
RO4	9	1653.5	0.005

Table 5
Fouling mitigation by different AOP pre-treatments

Water sample	Pre-treatment	Post-separation	Efficiency	Reference
Dye wastewater	Photocatalytic oxidation (UV = 24 W, catalysis TiO_2)	UF, RO	Flux decline reduction of UF (12%) and RO (8%)	[33]
UF permeate from NEWater factory	$O_3 + H_2O_2$ ($HiPO_X$)	RO	Improvement of TOC, color, and UV_{254}, suppression of organic and biological fouling	[19]
Landfill leachate	Fenton process (H_2O_2/Fe^{2+})	MF and NF	High efficient removal of COD, color, and humic substances before membrane separation	[34]
Synthetic humic solution	Heterogeneous catalytic ozonation (catalysis TiO_2)	Ceramic membrane (MW cut-off of 5 kDa)	Preventing membrane fouling and the formation of THMs effectively	[35]
Olive mill wastewater	Fenton-like (H_2O_2/Fe^{3+})	NF, RO	Enhancing the threshold flux and inhibiting membrane fouling	[13]
Groundwater	H_2O_2/UV (UV = 16 W)	NF	Mitigating organic and biological fouling significantly	[23]
Textile wastewater	H_2O_2/UV (UV = 128 W)	RO	Decreasing SDI and increasing permeate flux	[22]
Soluble algal organic matter solution	H_2O_2/UV (UV = 39 W)	MF	Mitigating the fouling of a ceramic MF membrane effectively	[3]
Municipal wastewater	Two-stage H_2O_2/UV (7.3 W*2)	RO	Inhibiting the organic and biofouling and mitigating the permeate flux decline obviously	This study

Table 6
Water quality for different treatment processes and regulatory reuse criteria

Item	BOD (mg/L)	COD (mg/L)	TOC (mg/L)	SS (mg/L)	Turbidity (NTU)	Total Coliform (CFU/100 mL)	Color (ADMI)	SDI
Secondly effluent	21	57	18	23	125	420,000	47	–
1 μm treatment	17 (19.0)	49 (14.0)	1.0 (5.6)	14 (39.1)	32 (74.4)	380,000 (0.04-log)	45 (4.3)	9.8
UV1 (60 = mg/L)	11 (46.7)	28 (50.9)	6.8 (62.2)	2.6 (88.7)	0.7 (99.4)	200 (3.32-log)	5 (89.4)	7.4
UV1 + UV2 (H_2O_2 = 20 mg/L)	7.8 (62.9)	16 (71.9)	2.98 (83.4)	1.9 (91.7)	0.43 (99.7)	190 (3.34-log)	3 (93.6)	4.7
UV1 + UV2 (H_2O_2 = 30 mg/L)	3.8 (81.9)	6.0 (89.5)	0.93 (94.8)	1.7 (92.6)	0.2 (99.8)	38 (4.04-log)	0 (100)	3.9
RO1	–	–	0.27 (98.5)	–	0 (100)	0 (100)	0.38 (99.2)	–
RO2	–	–	0.15 (99.2)	–	0 (100)	0 (100)	0 (100)	–
RO3	–	–	0.09 (99.5)	–	0 (100)	0 (100)	0 (100)	–
RO4	–	–	0.05 (99.7)	–	0 (100)	0 (100)	0 (100)	–
Taiwan EPA effluent standard	30	100	—	30	—	200,000	—	—
Toilet flushing or landscape irrigation reuse suggestion	10	—	—	—	2	200	No discomfort color	—
Reuse by the community	5	—	2.5	—	—	200	10	—
Drinking water resource standard	—	25	4	—	—	20,000	—	—
Drinking water standard	—	—	—	—	2	6	5*	—

(·): removal or rejection (% or log reduction)
"–": not measured; "—": no regulatory criteria
"*": color measured by visual comparison method

ever, after UV1 (H_2O_2 = 60 mg/L) treatment, the organic parameters of BOD, COD, and TOC were respectively 11.0, 28.0, and 6.8 mg/L,with corresponding removal efficiencies of 46.7%, 50.9%, and 62.2%. The total coliform was reduced to 200 CFU/100 mL (3.32-logs reduction), indicating that the one-stage H_2O_2/UV process effectively reduced the organics and total coliform. However, the SDI value of 7.4 still did not meet the acceptable level of equal to or less than

5. In contrast, for the two-stage H_2O_2/UV process of UV1 + UV2 (H_2O_2 = 20 mg/L), the TOC and SDI were 2.98 mg/L and 4.7, respectively; the water quality was suitable for RO separation. Moreover, the UV1 + UV2 (H_2O_2 = 30 mg/L) process was very effective as the resulting removals of organic matter, total coliform, and SDI were 6 mg/L (89.5% removal), 38 CFU/100 mL (4.04-log reduction), and 3.9, respectively. The water quality complied with the Taiwanese effluent standard, land irrigation criteria, toilet flushing standard, and drinking water resource standard and was also suitable for RO-post separation.

The TOC, total coliform, and color were very low for the RO1 process. However, the associated *r* value was only 36% after filtration for 30 h. For RO2 (one-stage H_2O_2/UV), the residual TOC was only 0.15 mg/L; the total coliform and color were zero. This indicated that the water quality met all of the reuse criteria and drinking water resource standards, except membrane fouling could still occur as the SDI value was too high. However, by combining two-stage H_2O_2/UV with RO separation (i.e., RO3 and RO4), the treated wastewater not only met all the reuse criteria and drinking standards but also prolonged the membrane life considerably.

4. Conclusions

Wastewater reuse is beneficial to the environment and is essential for combating water scarcity. In this study, the approach of H_2O_2/UV pre-oxidation combined with RO post-separation was evaluated to reuse municipal wastewater. The results showed that the two-stage H_2O_2/UV process was more effective than the one-stage process for mitigating RO membrane fouling. Furthermore, the two-stage H_2O_2/UV process not only had high disinfection and mineralization efficiencies but also decreased the SDI and effectively inhibited fouling. Thus, the problem of permeate flux of the subsequent RO membrane was greatly improved. The wastewater treated by this combination resulted in water of high quality that met the standards of reuse in Taiwan, implying that the method is both efficient and environmentally friendly.

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