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Figure-of-merit analysis of treating wastewater from color filter fabrication using H_2O_2/UV process for reuse

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ABSTRACT

In this study, the energy consumption and the operation cost of using the H_2O_2/UV process to treat wastewater from the color filter (CF) fabrication were evaluated by the electrical energy per order (E_{EO}). The results showed that both decolorization and mineralization followed the pseudo-first-order reaction. For the UV power of 13 W, as the H_2O_2 dose increased from 50 to 150 mg/L, E_{EO} reduced from 26.5 to 12.8 kW h m^{-3} order^{-1} for total organic carbon (TOC) and from 11.3 to 5.7 kW h m^{-3} order^{-1} for color. That is, by increasing the amount of H_2O_2, the electrical energy efficiency became better due to faster reaction as shown by the larger reaction constant k. Moreover, the electrical energy efficiency was better for the removal of color than for the removal of TOC as $E_{EO,TOC} > E_{EO,color}$. Moreover, irrespective of TOC and color removals, the E_{EO} values for both UV intensities of 13 and 9 W were close to each other, implying that a higher intensity could be applied by saving the operation time. Through the obtained E_{EO}, the achievable optimum costs to treat CF wastewater for reuse were 0.713 US\$/m^3 for decolorization and 1.214 US\$/m^3 for mineralization.

Keywords: Color filter; H_2O_2/UV; Energy consumption; Figure-of-merit; Reuse

1. Introduction

Currently, with the demand of light weight and mobility, thin-film transistor-liquid crystal displays (TFT-LCDs) are the dominant displaying devices. Following the success in information technology, Taiwan also has a strong display industry. In the manufacturing process of TFT-LCDs, the fabrication of color filter (CF) is an indispensable step because white lights are the typical light source for the color display. CF is always deposited on a clear glass substrate which typically includes the black matrix, CF layer, overcoat layer, and indium tin oxide film [1–3]. In order to obtain CF of good quality, a large amount of purified water is needed as the CF fabricating process uses lots of photo resists, organic solvents, and pigments. This ends up with a large amount of wastewater. The wastewater needs to be treated either for meeting the discharge requirements or for reuse. Presently, Taiwan's law demands 70% water reuse for all factories in the Industrial Parks, including the CF industry. However, the wastewater from the CF fabrication is

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hard to treat for reuse by traditional wastewater treatment technologies such as chemical coagulation and biological treatment. Hence, in this study, advanced oxidation processes (AOPs) are considered.

AOPs have been applied to remove resistant, toxic, and poorly biodegradable pollutants from water and wastewater. AOPs are defined as those oxidation treatments based on the reaction of hydroxyl radical ($HO^\bullet$) in an aqueous solution. The radical is a powerful and extremely reactive oxidant that can destroy organic pollutants efficiently. Among the AOPs, H_2O_2/UV oxidation is less pH dependent and generates no chemical sludge as compared to Fenton process [4,5]. Further, the processes of photochemical wastewater treatment depend on the addition of auxiliary oxidants, such as H_2O_2 and O_3. However, owing to the instability of the O_3 molecule, it can neither be shipped nor stored in gas tanks and has to be produced on site by special non-equilibrium electrical gas discharges. In contrast, aqueous solutions of H_2O_2 are easy to handle and are mainly used for oxidation reactions, including bleaching processes, chemical syntheses, and AOPs for water and wastewater treatment [6,7]. The effectiveness of H_2O_2/UV is primarily due to the presence of hydroxyl radicals which are created by direct photolysis of H_2O_2 under UV irradiation as Eq. (1). This process has been successfully employed in water and wastewater treatments [8–15] and was adopted in this study.

$$H_2O_2 + hv \rightarrow 2HO^\bullet \tag{1}$$

H_2O_2/UV degradation of aqueous organic pollutant is an electrical energy intensive process. Therefore, electrical energy is a major fraction of the operation cost. Thus, a simple figures-of-merit analysis based on the electrical energy consumption per m^3 per order of magnitude (E_{EO}) would be useful and informative for cost evaluations [5,16,17]. To date, no literature has focused on the energy consumption evaluation and cost analysis of real wastewater of CF fabrication. Thus, in this study, the H_2O_2/UV oxidation process was applied to evaluate the feasibility for CF wastewater reuse. The operation parameters included UV intensity (9 and 13 W) and H_2O_2 dose (50, 100, and 150 mg/L). In addition, the reaction constant, energy consumption, and operation cost were examined in this study.

2. Materials and methods

2.1. CF wastewater

The CF wastewater was sampled from a renowned CF factory located at the Tainan Technology Industrial Park, Taiwan. There are three types of wastewater from this factory including acid-based wastewater, organic wastewater, and sanitary sewage. In this study, organic wastewater was the target. The organic wastewater was treated first by pH adjustment, chemical coagulation, biological contact aeration, and rapid gravity filtering before discharge. The discharged wastewater was collected for further H_2O_2/UV oxidation treatment for possible in-factory reuse. The quality of the collected effluent was pH of 7.1, chemical oxygen demand (COD) of 42 mg/L, total organic carbon (TOC) of 10.2 mg/L, color of 65 ADMI (American Dye Manufacturers Institute) unit, and UV_{254} absorbance of 0.172 cm^{-1}.

2.2. Experimental methods

A stainless steel circular cylinder batch photo reactor was used (Chensun Engineering Co. Ltd) as shown in Fig. 1. The dimension was 9.8 cm (inner diameter) by 20.0 cm (height). A low-pressure UV lamp with a height of 12.8 cm of either 9 or 13 W (PHILIPS), irradiating mostly 254-nm wavelength, was installed at its center. The lamp was enclosed inside a quartz tube of 15.4 cm in height and 4.3 cm in diameter to fully utilize the emitted radiation. The volume of the reactor was about 1.2 L with water sample of 1 L for each experiment. Water was recirculated from the lower portion to the upper part of the reactor by a specially designed electric motor system so that both

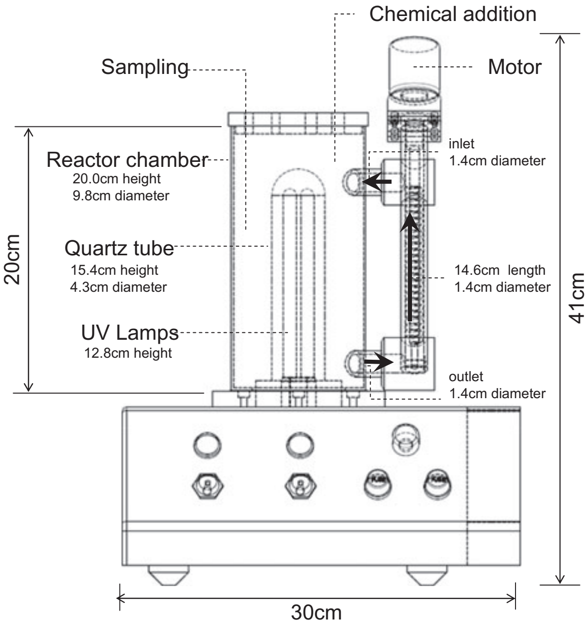

Fig. 1. Experimental setup of the batch photo reactor.

flow speed and gravity could be utilized for mixing and cooling. At the beginning of each experiment, H_2O_2 (35% w/w, Chang-Chun Petrochemical Co. Ltd) was added into the water sample. All the experiments were conducted at room temperature.

2.3. Chemical analysis

The pH, COD, TOC, and color were measured according to the procedures of Standard Methods [18]. TOC was determined by the TOC analyzer (model 700, O.I. Cooperation). Color was measured by the ADMI Tristimulus Filter Method using UV–vis spectrophotometer (Model U-2001, Hitachi). Prior to color measurement, water samples were filtered through a cellulose acetate membrane filter (ADVANTEC®, Japan) with pore size of 0.45 µm. In addition, the organic molecular weight (MW) distribution was measured by ultrafiltration under the pressure of 20 psi through hollow fiber membranes with MW cut-offs of 100 K and 10 K Daltons (Da) (A/G Technology Corporation), respectively. The MW range of larger than 100 k Da, 100 k–10 k Da, and smaller than 10 k Da was regarded as high, medium, and low MW fractions, respectively.

3. Results and discussion

3.1. Water quality of CF wastewater

The quality of CF wastewater was shown in Table 1, also included were Taiwan's effluent standard and in-factory reuse criteria for comparison. It can be observed that pH, COD, TOC, and color of the effluent were 7.1, 42, 10.2 mg/L, and 65 ADMI, respectively. It is evident that the effluent quality met Taiwan's effluent standards of pH of 6–9, COD of 100 mg/L, and color of 550 ADMI. However, the quality still did not meet the in-factory rinsing reuse criteria of TOC being 0.4 mg/L and color being 2 ADMI. Hence, further treatment ought to be applied to reduce TOC from 10.2 to 0.4 mg/L and color from 65 to 2 ADMI; that is, the required removals of TOC and color were 96 and 97%, respectively.

Moreover, the MW distribution of TOC of the effluent shown in Fig. 2 indicates that the high, medium, and low MW fractions were 12% (1.2 mg/L), 8% (0.8 mg/L), and 80% (8.2 mg/L), respectively. That is, TOC of the effluent contained mainly low MWs. Similarly, the percentages of color attributable to the high, medium, and low MW fraction in the effluent were 18% (12 ADMI), 15% (10 ADMI), and 67% (43 ADMI), respectively, also concentrated on the low MWs. These results are expected as the effluent was collected after chemical coagulation, biological contact aeration, and rapid gravity filtering as described in Section 2.1. Therefore, the process of H_2O_2/UV was taken to further oxidize organics with the goal of treating effluent to meet in-factory reuse criteria.

3.2. Effect of H_2O_2 dose and UV intensity

In this study, it was assumed that TOC and color were primarily degraded by hydroxyl radicals as described by Eqs. (2) and (3) for mineralization and decolorization, respectively. The subscript of k represents the reaction constant of the specific item, e.g. k_{TOC} denoting the reaction constant of TOC.

$$\mathrm{TOC} + \mathrm{HO}^{\bullet} \xrightarrow{k_{\mathrm{TOC}}} \mathrm{CO_2} + \mathrm{H_2O} \tag{2}$$

$$\text{Color constituents} + \mathrm{HO}^{\bullet} \xrightarrow{k_{\mathrm{color}}} \text{colorless products} \tag{3}$$

The results of TOC mineralization and decolorization are portrayed in Fig. 3 for UV of 13 W. For the H_2O_2 doses of 50, 100, and 150 mg/L, the corresponding oxidation times of 96% TOC removal were 150, 120, and 75 min, whereas those of 97% color removal were 75, 60, and 40 min. For UV of 9 W, the corresponding oxidation times of 96% TOC removal were 225, 180, and 120 min and those of 97% color removal were 105, 90, and 60 min, respectively. Hence, the overall trends in oxidation time for both UV intensities were the same, except that it took more time for UV of 9 W to reach the same level of removal for both TOC and color. Moreover, for both UV intensities, the oxidation time decreased with the increased H_2O_2

Table 1
Water quality of CF wastewater, Taiwan's effluent standard, and in-factory reuse criteria

Water quality	pH	COD (mg/L)	TOC (mg/L)	Color (ADMI)
CF wastewater	7.1 ± 0.05	42.0 ± 0.41	10.2 ± 0.02	65 ± 0.8
Taiwan effluent standard	6–9	100	–	550
In-factory rinsing reuse criteria	6.5–7.5	–	0.4	2
Required removal for reuse	–	–	96%	97%

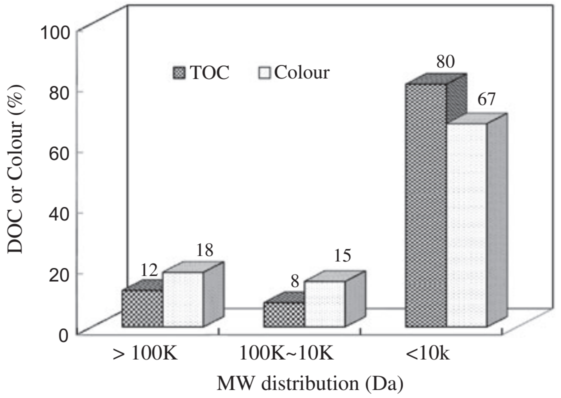

Fig. 2. MW distribution of CF wastewater.

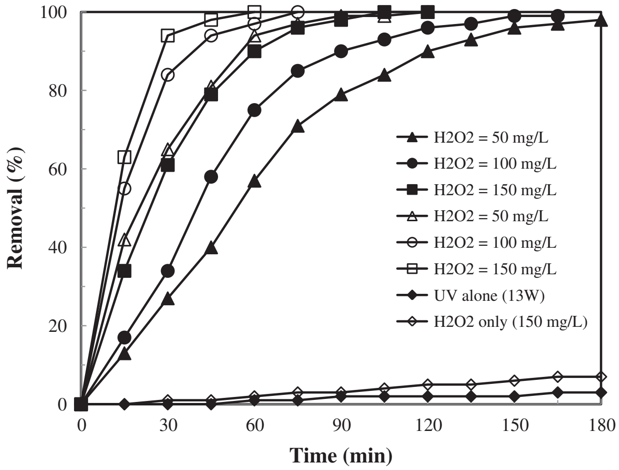

Fig. 3. TOC and color removals by H_2O_2/UV oxidation (UV = 13 W, solid symbols for TOC, and open symbols for color).

dose. These results were expected. Further, color removal was more efficient than that of TOC. This is because decolorization only needs to destroy the chromophore of organics, whereas mineralization requires transforming organics into CO_2 and H_2O as Eqs. (2) and (3). Also, it can be observed from Fig. 3 that the TOC or color removal was ineffective using only either UV or H_2O_2. The findings are similar to other studies. Many researchers showed that treating dye wastewater by UV irradiation alone was ineffective for color removal [12,19,20]. Similarly, Kang et al., showed the ineffectiveness of treating textile wastewater for color removal by only using H_2O_2 [21].

3.3. The reaction constant

The reaction equation is expressed by Eq. (4), where C_0 and C_t are TOC (or color) at oxidation times of 0 (initial time) and t min, respectively, and k is the pseudo-first-order reaction constant.

$$\ln(C_0/C_t) = kt \tag{4}$$

The reaction constants of TOC and color were determined by regression, piecewise linear for the former and linear for the latter, of the data depicted in Fig. 4 for H_2O_2 of 50, 100, and 150 mg/L using a semi-log scale. Two time intervals were used for the piecewise linear regression analysis of TOC. The first was $0 \le t \le 30$ min and the second was $t \ge 30$ min. The results are listed in Table 2 and indicated good linearity as evident from the large correlation coefficients. It is evident that the reactions of TOC were faster for the second time interval, irrespective of UV intensities or H_2O_2 doses, due to time required for the mineralization of DOC.

Moreover, the reaction constants of color were always larger than those of TOC, namely $k_{\text{color}} > k_{\text{TOC}}$, irrespective of H_2O_2 doses or UV intensities. That is, decolorization was more efficient than mineralization. This was due to the situation that decolorization was the destruction of chromophores (unsaturated or multiple bonds) of pigments (the source of color). Attacking unsaturated bonds by $HO^{\cdot}$ is easier than mineralizing organics to CO_2 and H_2O [22,23]. These results are similar to those of other researchers [24–26]. Also, increasing either H_2O_2 dose or UV intensity will result in a larger k which corresponds to faster reactions as expected.

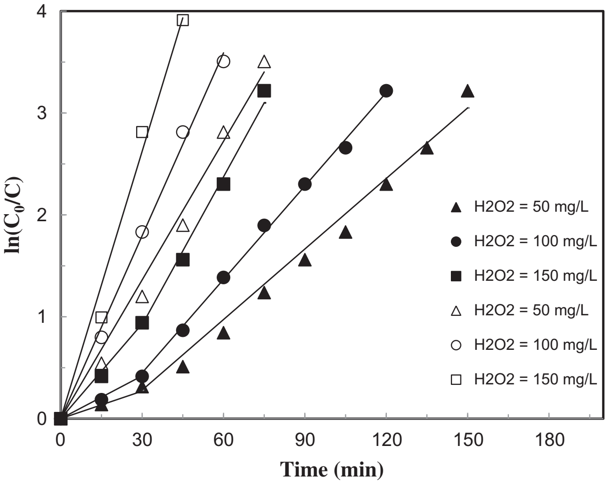

Fig. 4. Pseudo-first-order kinetics based on the data in Fig. 3 (UV = 13 W, solid symbols for TOC, and open symbols for color).

Table 2
Reaction constants of TOC and color

Process		TOC						Color		
H_2O_2 (mg/L)		50		100		150		50	100	150
Time (min)		≤30	≥30	≤30	≥30	≤30	≥30	0–75	0–60	0–45
13 W	k (min^{-1})	0.010	0.024	0.014	0.0307	0.031	0.051	0.044	0.060	0.087
	R^2	0.995	0.990	0.996	0.997	0.995	0.992	0.991	0.996	0.985
		≤30	≥30	≤30	≥30	≤30	≥30	0–25	0–15	0–15
9 W	k (min^{-1})	0.006	0.015	0.008	0.020	0.016	0.031	0.030	0.040	0.058
	R^2	0.980	0.996	0.991	0.995	0.996	0.999	0.989	0.996	0.993

3.4. Electrical energy consumption

The results given in Section 3.2 show that H_2O_2/UV was an effective process for TOC and color removals. Therefore, the related cost requirement was evaluated so that practical applications could be properly utilized. In this respect, several reports are available in the literature on electrical energy determination of various H_2O_2/UV processes. However, it is necessary to study the electrical energy consumption of H_2O_2/UV under different investigating conditions as energy consumptions are strongly dependent on UV intensity, oxidation time, H_2O_2 dose, and reactor configuration. Further, factors such as economics, effluent quality, etc., also play a vital role in selecting a wastewater treatment technology. Since H_2O_2/UV is a photo degradation process, the electrical energy and H_2O_2 dose are the primary operating costs. Therefore, the cost of electrical energy was addressed via E_{EO}.

Conventionally, E_{EO} is treated as the electrical energy required (in kW h) to reduce the pollutant concentration by one order of magnitude (i.e. 90% removal, $\log C_0/C = 1$) per 1 m^3 of wastewater and is defined by Eq. (5) [17]. The symbols C_0 and C denote the initial and 90% removal concentrations, respectively, whereas the UV dose is given by Eq. (6) [5,17,27]. Because E_{EO} represents the electrical energy required for the process, a smaller E_{EO} is more desirable as it implies a more efficient process and costing less electrical energy for accomplishing the treatment goal [24,28].

$$E_{EO}\left(\text{kW h m}^{-3}\,\text{order}^{-1}\right) = \text{UV dose}/\log(C_0/C) \tag{5}$$

$$\text{UV dose}\left(\text{kW h m}^{-3}\right) = \text{Lamp power (kW)} \times \text{time (h)} \\ \times 1000/\text{treated volume (L)} \tag{6}$$

As an example, the procedure of determining E_{EO} of TOC for UV intensity of 13 W and H_2O_2 of 50 mg/L is illustrated in Fig. 5 (data drawn by the solid triangle symbol). First, the concentration variation vs. UV dose was plotted. Then, the data were fitted by a two-degree polynomial through regression analysis. Finally, the UV dose corresponding to $\log C_0/C = 1$ (i.e. 90% removal) was marked (illustrated by the broken line in Fig. 5) to obtain the required UV dose (i.e. 26.5 kW h m^{-3}) for determining E_{EO} (i.e. 26.5 kW h m^{-3} order^{-1}). Through this procedure, all the E_{EO} results for both TOC and color removals were obtained and are shown in Fig. 6 for further examination.

From the results shown in Fig. 6, it can be noticed that the trends of reduction in E_{EO} vs. H_2O_2 dose for both 9 and 13 W are the same, irrespective of TOC and color. Specifically for UV of 9 W, by increasing the H_2O_2 dose from 50 to 150 mg/L, the values of E_{EO}

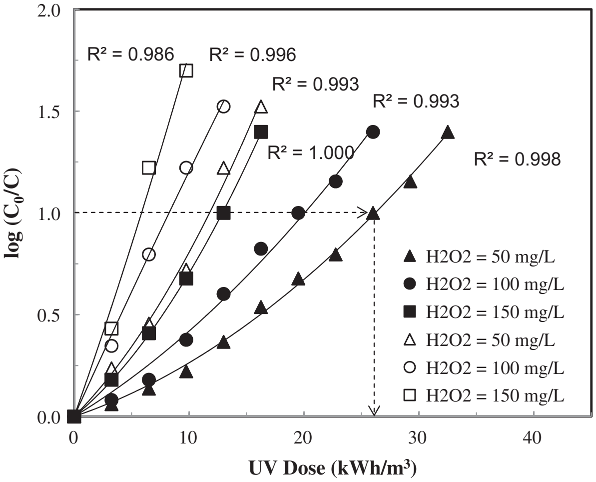

Fig. 5. E_{EO} determination for TOC and color (UV = 13 W, solid symbols for TOC, and open symbols for color).

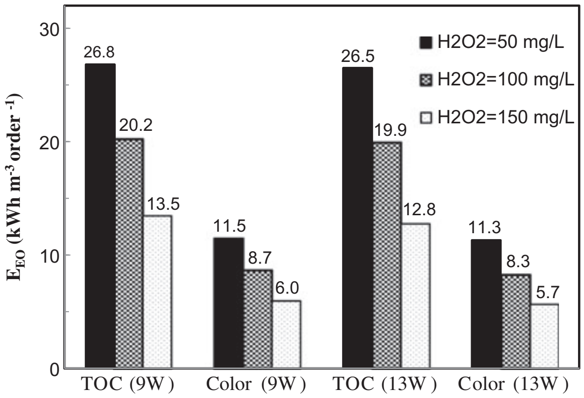

Fig. 6. E_{EO} of TOC and color.

reduced from 26.8 to 13.5 kW h m^{-3} order^{-1} for TOC and from 11.5 to 6.0 kW h m^{-3} order^{-1} for color. For UV of 13 W, the corresponding E_{EO} decreased from 26.5 to 12.8 kW h m^{-3} order^{-1} and from 11.3 to 5.7 kW h m^{-3} order^{-1}. That is, E_{EO} decreased by increasing the H_2O_2 dose, implying better electrical energy efficiency due to faster reaction as evident from the larger reaction constant k listed in Table 2 as expected. Moreover, $E_{EO,TOC} > E_{EO,color}$. That is, the electrical energy efficiency was better for color removal than for TOC removal. Further, irrespective of TOC and color removals, the E_{EO} values for both UV intensities of 13 and 9 W were close to each other, implying that a higher intensity could be applied by saving the operation time.

As a comparison for the energy consumption, Table 3 tabulates some results from the literature in which pollutants were treated by the H_2O_2/UV process. It can be observed that either E_{EO} or E_{EM} (electric energy per mass) was adopted, depending generally on the pollutant concentrations. Two features can be noticed. One is that the energy consumption and operation cost varied, depending on the nature of pollutants. The other was decolorization that was always more energy efficient than mineralization. It should be noted that E_{EO} obtained by Muruganandham et al. [5] was considerably larger than those of others. This was because, instead of 254 nm, the 356 nm UV they adopted had low absorption by H_2O_2 and resulted in low formation of $HO^{\bullet}$.

3.5. Operation cost analysis

Using the reduction conditions of 96% TOC and 97% color, the total operation cost was computed using 0.066 US$/kW h of Taiwan's electrical bill for industry and 0.33 US$/kg for the H_2O_2 dose. The results are shown in Table 4. As an example, the procedure of obtaining the result of operation condition 3 in Table 4 is illustrated as follows. Operation condition 3 included UV of 13 W, H_2O_2 of 150 mg/L, oxidation time of 75 min, and water sample of 1 L. The electrical energy expenditure was computed from the UV dose given by Eq. (6), namely

$$\begin{aligned}\text{UV dose (kW h m}^{-3}) &= \text{Lamp power (kW)} \times \text{time (h)} \\ &\quad \times 1000/\text{treated volume (L)} \\ &= 13/1000\ \text{(kW)} \times 75/60\ \text{(h)} \\ &\quad \times 1000/1\ \text{(L)} \\ &= 16.25\ (\text{kW h m}^{-3})\end{aligned}$$

Table 3
Comparison of energy consumption for H_2O_2/UV process

Refs.	Pollutants	Energy consumption	Cost
Yonar et al. [29]	Domestic wastewater	10 kW h/kg COD	US$ 0.17/m^3
Muruganandham et al. [5]	Reactive azo dye	RO4 dye: 1,666 kW h m^{-3} order^{-1} RYm14 m dye: 2,000 kW h m^{-3} order^{-1}	NA
Aleboyeh et al. [16]	Azo dye solution (C.I. Acid Orange 7)	Decolorization: 1.133–2.696 kW h m^{-3} order^{-1} Mineralization: 5.691 −12.1 kW h m^{-3} order^{-1}	Decolorization: 0.07–0.16 €/m^3 Mineralization: 0.34–0.73 €/m^3
Zalazar et al. [30]	Dichloroacetic acid	9.31 kW h/g TOC	NA
Shu et al. [28]	Micropollutants	1.3–7.1 kW h m^{-3} order^{-1}	NA
Yen et al. [31]	Electroplating wastewater	48 kW h m^{-3} order^{-1}	US$ 2.88/m^3
Yen and Yen [15]	Humic acid	Decolorization: 4.2 kW h m^{-3} order^{-1} Mineralization: 12.0 kW h m^{-3} order^{-1}	Decolorization: US$ 0.263/m^3 Mineralization: US$ 0.74/m^3

Table 4
Costs of electrical energy and H_2O_2 consumption

Operation condition	UV (W)	H_2O_2 (mg/L)	Time (min)	UV dose (kW h/m^3)	Electric energy cost (US\$/m^3)	H_2O_2[a] (kg/m^3)	H_2O_2 cost (US\$/m^3)	Total (US \$/m^3)	US \$/g TOC
TOC									
1	13	50	150	32.50	2.145	0.143	0.047	2.192	0.226
2	13	100	120	26.00	1.716	0.286	0.094	1.810	0.187
3	13	150	75	16.25	1.073	0.429	0.141	1.214	0.125
4	9	50	225	33.75	2.228	0.143	0.047	2.275	0.234
5	9	100	180	27.00	1.782	0.286	0.094	1.876	0.193
6	9	150	120	18.00	1.188	0.429	0.141	1.329	0.137
Color									
Item	UV (W)	H_2O_2 (mg/L)	Time (min)	UV dose (kW h/m^3)	Electric energy cost (US\$/m^3)	H_2O_2 (kg/m^3)	H_2O_2 cost (US\$/m^3)	Total (US \$/m^3)	US \$/ADMI
7	13	50	75	16.25	1.073	0.143	0.047	1.120	0.115
8	13	100	60	13.00	0.858	0.286	0.094	0.952	0.098
9	13	150	40	8.67	0.572	0.429	0.141	0.713	0.074
10	9	50	105	15.75	1.040	0.143	0.047	1.087	0.112
11	9	100	90	13.50	0.891	0.286	0.094	0.985	0.102
12	9	150	60	9.00	0.594	0.429	0.141	0.735	0.076

[a] The purity of H_2O_2 was 35%.

$$\text{Electrical energy cost} = 16.25\ (\text{kW h m}^{-3}) \times 0.066\ (\text{US\$/kW h}) = 1.073\ (\text{US\$/m}^3)$$

Also, as H_2O_2 of 150 mg/L being 0.15 kg/m^3, the H_2O_2 cost is:

$$H_2O_2\ \text{cost} = 0.15\,\text{kg/m}^3 \times 0.33\,\text{US\$/kg} \div 0.35 = 0.141\,\text{US\$/m}^3$$

In which, the factor 0.35 was due to the concentration of H_2O_2 being 35%. Hence, the total cost is:

$$\begin{aligned}\text{Total cost} &= \text{Electrical energy cost} + H_2O_2\ \text{cost}\\ &= 1.073\,\text{US\$/m}^3 + 0.141\,\text{US\$/m}^3\\ &= 1.214\,\text{US\$/m}^3\end{aligned}$$

Table 4 and Fig. 7 show that the costs for TOC removal were 1.214–2.275 US\$/m^3 (0.125–0.234 US \$/g TOC), whereas those for color were 0.713–1.120 US\$/m^3 (0.074–0.112 US\$/ADMI). For clarity, in both Table 4 and Fig. 7, the operations are divided into two groups: conditions 1–6 for TOC and 7–12 for color. It is evident that decolorization was more economic than mineralization, irrespective of electrical energy or H_2O_2 cost. The result was the same as those of our previous study [15] and Aleboyeh et al. [16] which are also listed in Table 3 for comparison. In addition, the results are consistent with those of the reaction constants and E_{EO} described above. It can also be observed that electrical energy costs reduced as H_2O_2 dose increased due to higher efficiency as expected. However, for TOC removal, the total cost was the smallest with H_2O_2 dose of 150 mg/L for both UV intensities of 13 and 9 W. On the other hand, the rate of decolorization or mineralization increased with increasing concentrations of H_2O_2 up only to a threshold value; afterward, the rate declined due to scavenging reaction of H_2O_2 [16,32].

In this study, even though both operation costs of TOC and color removals were more expensive than that of water for Taiwan industry of US\$ 0.33/m^3, the

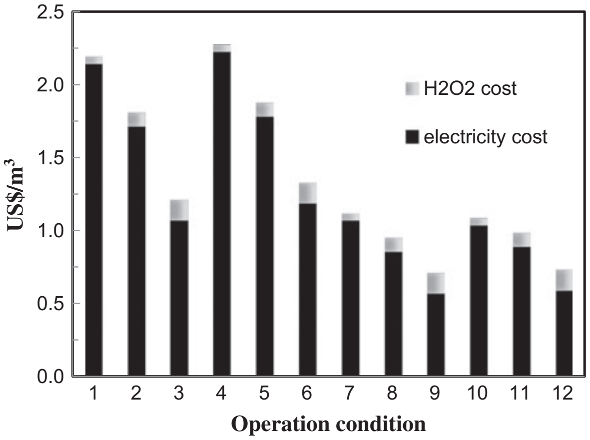

Fig. 7. Costs per m^3 of treated water vs. operation conditions of Table 4.

scarcity of water resource cannot be ignored. Hence, wastewater reuse is imposed by law in Taiwan.

4. Conclusion

The study employed the H_2O_2/UV process to treat wastewater from CF fabrication for reuse. The related energy cost was assessed by E_{EO}. Key results are as follows.

Firstly, both decolorization and mineralization processes followed the pseudo-first-order reaction. Secondly, the reaction for color removal was faster than that of TOC removal. Specifically, under the condition of UV power of 13 W, by increasing the H_2O_2 dose from 50 to 150 mg/L, E_{EO} reduced from 26.5 to 12.8 kW h m^{-3} $order^{-1}$ for TOC and from 11.3 to 5.7 kW h m^{-3} $order^{-1}$ for color. Hence, the electrical energy efficiency was better for the removal of color than for the removal of TOC as $E_{EO,TOC} > E_{EO,color}$. Last, the achievable optimum operation costs to treat CF wastewater for reuse were 0.713 US\$/m^3 for decolorization and 1.214 US\$/m^3 for mineralization.

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