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Monitoring and control of UV and UV-TiO_2 disinfections for municipal wastewater reclamation using artificial neural networks

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ABSTRACT

The use of ultraviolet (UV) irradiation as a physical wastewater disinfection has increased in recent years, especially for wastewater reuse. The UV-TiO_2 can generate OH radicals, which is highly effective to inactivate microorganisms in wastewater disinfection. However, both UV and UV-TiO_2 disinfections create multiple physical, chemical, and bio-chemical phenomena that affect their germicidal efficiency. It is difficult to build a precise control model using existing mathematic models. This study applies artificial neural network (ANN) models to control UV and UV-TiO_2 disinfections. Experimental results indicate that the ANN models, which precisely generate relationships among multiple monitored parameters, total coliform counts in influent and effluent, and UV doses, can be used as control models for UV and UV-TiO_2 disinfections. A novel ANN control strategy is applied to control UV and UV-TiO_2 disinfection processes to meet three total coliform count limits for three wastewater reuse purposes. The proposed controlled strategy effectively controls UV and UV-TiO_2 disinfection, resulting in acceptable total coliform counts in effluent for the three wastewater reuse purposes. The required UV doses for UV-TiO_2 disinfection were lower than those for UV disinfection, resulting in energy saving and capacity reduction of 13.2–15.7%.

1. Introduction

Due to water shortages, wastewater recycling and reclamation has been regarded as critical to sustainable use of global water resources [1,2]. Effective wastewater disinfection to generate the safe water qualities is one of the most important processes in wastewater reclamation. The use of UV irradiation as a physical process for water and wastewater disinfection has increased in recent years due to its many advantages—no chemicals are needed, response time is short, and operation is safe [3–7]. Notably, UV irradiation eliminates enteric bacteria, viruses, bacterial spores, and parasite cysts, and is an effective wastewater disinfection technique, especially for water reuse and reclamation [8–10].

Additionally, UV-TIO_2 photocatalytic disinfection combines TiO_2 with UV, which can generate reactive oxygen species such as OH radicals, superoxide anions, and hydrogen peroxide. These reactive oxygen species, especially OH radicals, are highly effective in inactivating microorganisms in wastewater. Therefore, photocatalysis by UV-TiO_2 is regarded as an alternative or a complement to conventional water and wastewater disinfection methods [11–14]. A TiO_2-coated surface is commonly utilized when developing TiO_2-based photocatalytic disinfection systems [15–17].

The germicidal efficiencies of both UV and UV-TiO_2 systems depend markedly on multiple parameters, including influent water quality, and control factors including influent suspended solids (SS) or turbidity, water temperature, pH in reactor, UV light intensity, and contact time [18–20]. Artificial neural networks (ANNs), back-propagation neural networks (BPNs) particularly, have been widely and effectively applied for process monitoring and control of wastewater treatments. The ANN models have been used for process control of chlorination of wastewater [21], Fenton oxidation [22], sludge hygienization [23]; the ANNs also applied to predict the chlorine decay in water distribution [24], to predict the disinfection by-product in chlorination of drinking water [25], to evaluate the performances of water and wastewater plants [26,27]. ANN models can precisely predict the behavior of complex nonlinear systems, and are particularly useful for process monitoring and control of wastewater treatments. Therefore, the ANN models using multiple parameters were applied to build control models in this study.

Finally, another series of disinfection experiments was conducted to verify the efficacy of the proposed control strategy. In this study, both UV disinfection and UV-TiO_2 photocatalytic disinfection devices were established in laboratory-scale for a series of wastewater disinfection experiments. The parameters—turbidity, pH, temperature, oxidation–reduction potential (ORP), and UV light intensity—in the reactor were monitored online to build the optimal control strategy.

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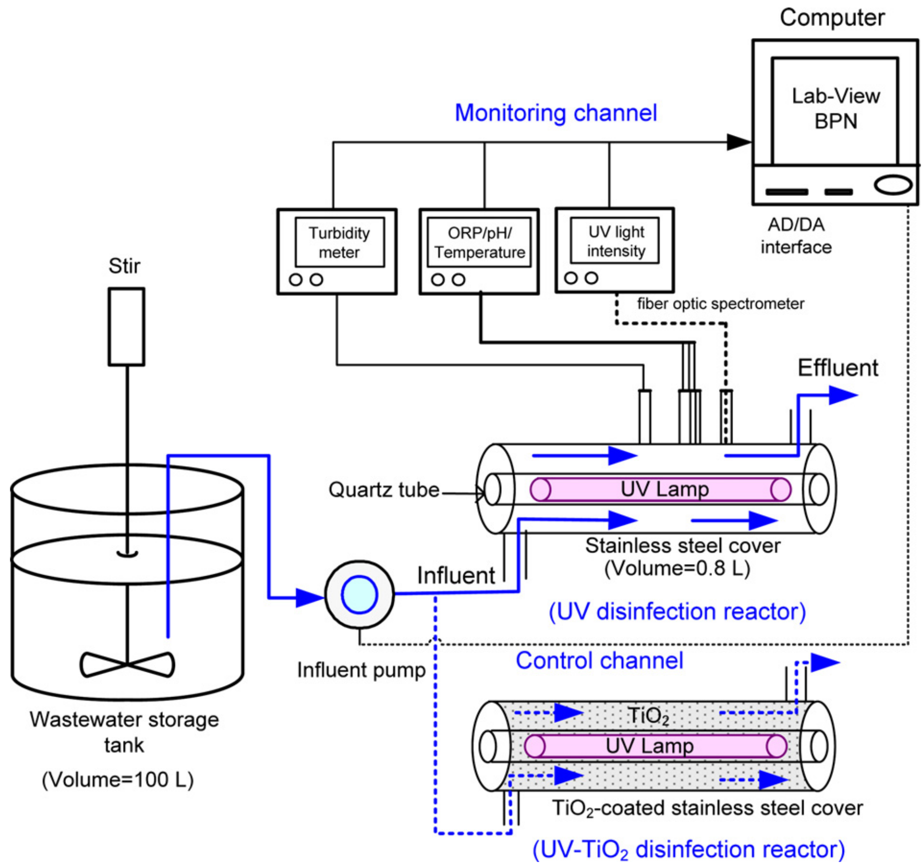

Fig. 1. Schematic diagram of the UV and UV-TiO_2 disinfection systems in this study.

2. Materials and methods

2.1. UV and UV-TiO_2 disinfection reactor and monitoring system

Laboratory-scale UV and UV-TiO_2 disinfection systems were set up as continuous-flow reactors in this study. Fig. 1 shows a schematic diagram of the UV and UV-TiO_2 disinfection systems, including effective reactor volumes and monitoring and control units. A tank with a mechanical mixer, which had an effective volume of 100 L, was used for storage and to provide influent wastewater to the disinfection system. Real wastewater samples from the Miao-Li City sewer system, Taiwan, were used in this work. The samples had total coliform counts of roughly 10^5–10^6 CFU/100 mL. Table 1 lists the typical concentrations of the main constituents in these real wastewater samples. A peristaltic computer-controlled pump (Master Flex, USA) pumped the stored wastewater into the disinfection reactor at different flow rates to regulate contact times. The stainless steel UV disinfection reactor had an effective volume of 0.8 L. A 4-W low-pressure mercury UV lamp (Philips/G4, Holland) covered by a quartz tube was installed inside the reactor. Another UV-TiO_2 disinfection reactor, which had the same configuration as the UV disinfection reactor, except that TiO_2 powder (Degussa P-25; Germany), which had an average diameter of 30 μm and the BET surface area of 50 ± 15 m^2/g, coated in the inner surface of the stainless cover, which had a density of 0.3 mg/cm^2.

The pH, ORP, and temperature meters with sensors (Mettler Toledo, Switzerland) were installed in the reactors. A turbidity meter (WTW, MIQ/S 184-H3, Germany) was also installed in the reactor. The UV light intensity (WL = 254 nm) in the reactor was detected by a fiber-optic spectrometer (EPP 2000C; StellarNet, USA). All meters and pumps were connected to a personal computer (PC) for online monitoring and process control. The software for data acquisition and process control was programmed using LabVIEW 7.1 (National Instruments, USA).

2.2. Experimental

Two series of UV and UV-TiO_2 disinfection experiments were carried out. The first series of experiments, using a wide range of operating conditions, was conducted to identify the characteristics of UV and UV-TiO_2 disinfection and monitoring parameters as well as building the BPN control models. Another series of experiments was conducted to verify the proposed BPN-based control

Table 1
Water qualities of the real wastewater samples used in this study.

Total-P (mg/L)	NH_3-N (mg/L)	NO_2-N (mg/L)	NO_3-N (mg/L)	SO_4^- (mg/L)	Turbidity (NTU)
0.62–0.75 (0.66)[a]	0.5–2.5 (1.75)	0.03–0.23 (0.07)	0.63–1.76 (1.21)	12.78–22.42 (17.6)	1.98–4.57 (3.53)

BOD_5 (mg/L)	COD (mg/L)	SS (mg/L)	pH	DO (mg/L)	Conductibility (μs/cm)
2.1–7.4 (3.3)	5.2–21.7 (8.3)	1.4–26.4 (11.1)	7.3–8.6 (7.7)	4.5–8.1 (6.2)	334–512 (413)

[a] () means the average.

models. The three wastewater reuse standards for total coliform count in Taiwan were set as control targets. Due to that residual suspended solids in treated wastewater will decrease the germicidal efficiencies of UV disinfection; a pre-study was also conducted to investigate the influence of solids concentrations on UV germicidal efficiencies.

Real domestic wastewater samples were continuously pumped into the UV or UV-TiO_2 disinfection reactor at 13 influent flow rates in the range of 400–1840 mL/min^{-1} to generate 13 different contact durations in the range of 26–120 s. Thus, 13 different UV dosages in the range of 3502–17,996 μW s/cm^2 were used in disinfection experiments. The monitored UV light intensity near the reactor surface was used to calculate the UV dose. Thus, the calculated UV doses in this work were relatively lower than UV doses in similar studies. After a 20-min period for stabilizing the UV disinfection systems, all experiments were conducted during the following 60 min; thus, the overall duration of experiments was around 80 min. Another 80-min experiment was conducted sequentially for UV-TiO_2 disinfection. After the reactor stabilized, influent and effluent samples were collected to analyze their quality using Standard Methods [28]. The total coliform counts in influent were measured at the start and end of each experiment, and total coliform counts in effluent were measured every 5–10 min using the Membrane Filter Method (9222 B), the color of samples were also measured by ADMI tristimulus method (2120E). The UV intensity, turbidity, ORP, pH, and temperature in the disinfection reactor were monitored online simultaneously. In total, 84 runs of UV and UV-TiO_2 disinfections were conducted in this study, respectively.

2.3. ANN control model

A typical BPN model has three layers—the input, hidden, and output layers. The BPN model in this work was developed using PCN_4 software and utilized to construct control models [29]. This BPN model uses the generalized delta-learning rule as the training algorithm, the gradient descent method to minimize error, and root mean square (RMS) to evaluate the performance of training and test procedures.

3. Results and discussion

3.1. Influences of suspended solids on UV disinfection

As residual suspended solids in wastewater will block UV light and decrease germicidal efficiency of UV disinfection, the effects of SS on UV disinfection were investigated in the pre-study. According to White [19], SS do not interfere with UV disinfection when its concentration is <10 mg/L. Suspended solids collected from the same sewer system was added into the prepared wastewater samples in the pre-study, typically with diameters <100 μm, to increase SS concentrations to roughly 10–70 mg/L, which are close to the effluent standard limit of 30 mg/L in Taiwan. In this pre-study, influent wastewater contained total coliform counts of around 10^5–10^6 CFU/100 mL. After UV disinfection with doses of 2500–32,800 μWs/cm^2, the effluent coliform counts declined to around 0–12,800 CFU/100 mL (Fig. 2). The effluent coliform counts were less than 10 CFU/100 mL when UV doses exceeded 16,000 μW s/cm^2. The suspended solids in wastewater did not affect the efficiency of UV disinfection with this high UV dose. However, decreases in disinfection efficiency due to suspended solids were obvious when UV doses were <12,000 μW s/cm^2. Higher concentrations of suspended solids caused more significant germicidal efficiency decrease. This reduction in UV germicidal efficiency was caused by SS reducing UV light penetration.

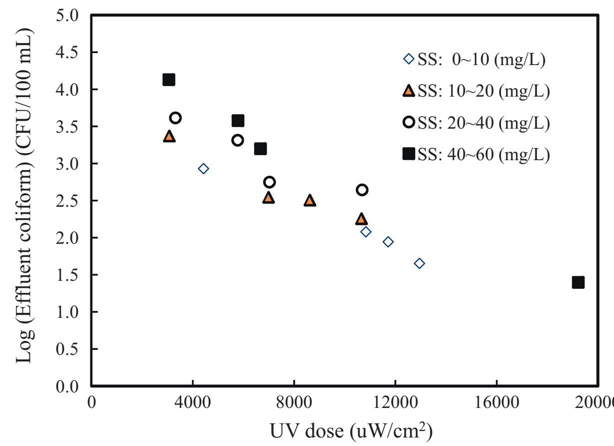

Fig. 2. Influences of suspended solids on germicidal efficiency of UV disinfection in the pre-study.

In this relatively narrow concentration range for SS of 10–70 mg/L, monitored turbidities increased as measured SS concentrations increased, generating an acceptable linear relationship (Fig. 3). Therefore, monitored turbidity replaced measured SS in the following control studies.

3.2. Germicidal efficiency and characteristics of UV and UV-TiO_2 disinfection

Table 2 summarizes operational conditions, monitoring data, measured total coliform counts in influent and effluent from the UV and UV-TiO_2 reactors in the first series of UV and UV-TiO_2 disinfection experiments. Average total coliform counts in influent wastewater samples were 1.8–4.8 × 10^5 CFU/100 mL (average, 2.4 × 10^5) and 1.7–4.9 × 10^5 CFU/100 mL (average, 2.7 × 10^5) After disinfections, the effluent coliform counts decreased to 0–15,500 CFU/100 mL (average, 3741) and 0–13,000 CFU/100 mL (average, 1569), for UV and UV-TiO_2 disinfection, respectively. It was found that UV-TiO_2 disinfection was more effective than UV disinfection in reducing coliform counts (Fig. 4).

The kinetics of coliform inactivation by UV radiation are typically close to the following second-order kinetic reaction [7,19,30]:

$$\frac{N_t}{N_0} = e^{kP_d t} \quad (1)$$

where N_0 is initial coliform count, N_t is surviving coliform count at time t (CFU or MPN/100 mL), k is the rate constant, P_d is UV intensity (uW/cm^2), and t is exposure time (s).

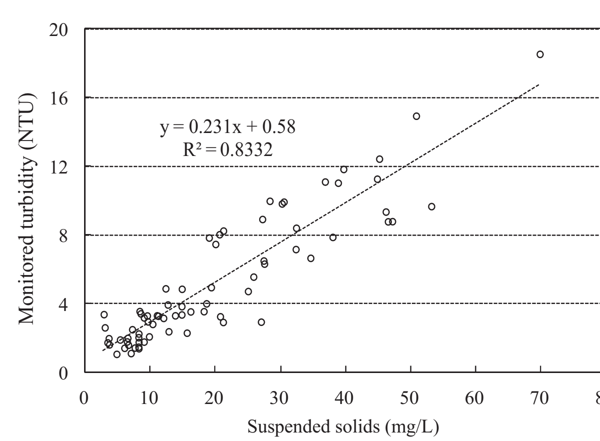

Fig. 3. Linear relationship between monitored turbidities with measured SS concentrations.

Table 2
Summary of the operational conditions, monitoring data, measured influent and effluent total coliform counts of UV and UV-TiO_2 reactors in this study.

Reactor	Contact time (s)	UV intensity (W/m^2)	UV dose ($\mu W\,s/cm^2$)	Suspended solids (mg/L)	Color (ADMI)	Turbidity (NTU)	ORP (mV)	pH	Temperature (°C)	Total coliform counts (CFU/100 mL)	
										Influent	Effluent
UV	26–120	1.34–1.50	3502–17,865	6.1–36.7	11–63	2.01–6.55	8.4–67.7	7.74–8.33	22.3–25.1	180,000–482,500	0–15,500
UV–TiO_2	26–120	1.31–1.50	3545–17,996	5.6–27.9	16–61	2.06–14.97	42.2–274.1	7.79–8.33	22.1–25.1	175,000–485,000	0–13,000

However, only acceptable linear relationships between $\log(N_t/N_0)$ with UV dose for UV and UV-TiO_2 disinfection existed (Fig. 4). The rate constant k for UV disinfection was very close to that in the study by Scheible and Bassel [31]. This finding also indicates that the generally used second-order kinetic cannot comprehensively present the correlations of coliform inactivation by UV and UV-TiO_2 radiation. As multiple biochemical and physical factors affect UV disinfection, the UV and UV-TiO_2 disinfection processes are both complex and dynamic. Some other nonlinear coliform/pathogen kill models have been proposed and discussed [5]. However, building a simple and precise coliform kill model, especially for process control purposes, is extremely difficult.

The monitoring of ORP and pH has been widely used for process control in wastewater treatment [32]. Fig. 5 presents monitored ORP and pH values in the UV and UV-TiO_2 disinfection reactors. The ORP values in the UV-TiO_2 reactor were significantly higher than those in the UV reactor due to the hydroxyl radicals generated by the photocatalytic reaction in the UV-TiO_2 system. Typically, ORP values increased as UV doses increased in the UV-TiO_2 reactor; however, ORP values decreased slowly as UV doses increased in the UV reactor. The pH values and temperatures in the UV disinfection reactor were stable and very close to those in the UV-TiO_2 reactor (Fig. 5).

3.3. BPN control model and strategy

As UV and UV-TiO_2 disinfection processes are complex nonlinear systems containing both bio-chemical and physical phenomena, using typical mathematic models as control models for UV or UV-TiO_2 disinfection is difficult. Therefore, the BPN models were used to construct the control model based on experimental results from the first series. Two BPN models were constructed using eight input parameters to predict effluent coliform counts for UV and UV-TiO_2 disinfection, respectively. Table 3 lists input/output parameters, network architectures, optimization algorithms, and prediction results by the BPN models. For UV and UV-TiO_2 disinfection data simulation, 55 data sets were randomly selected from 84 runs of experimental results as training samples and the remaining 29 sets were used as testing samples in the BPN models.

Fig. 6 shows correlations between predicted and measured effluent coliform counts by the two BPN models. Precise prediction results with correlation coefficients (R^2) of 0.92 and 0.95 for UV and UV-TiO_2 disinfections, respectively, were obtained (Table 3). This experimental finding indicates that these BPN models can be used as control models for UV and UV-TiO_2 disinfection.

Fig. 7 shows the proposed UV and UV-TiO_2 disinfection control strategy. When the prepared wastewater sample was pumped from the storage tank into the UV or UV-TiO_2 reactor, the initial UV dose was determined using the equation in Fig. 4. Because the UV lamp used in this study has a fixed power of 4 watts, its initial light intensity is fixed. A computer-controlled peristaltic pump was used to regulate different flow rates or contact time to generate different UV doses. After 15–20 min, which is around ten times of contact time, to reach a stable condition, the BPN control models were activated to predict coliform counts in effluent using the eight parameters (Table 3), and the predicted coliform counts were then compared to the control targets. When the predicted effluent coliform counts was in an acceptable range, typically <20–30% of the control target, the UV dose was implemented or held; otherwise, a tuning on UV dose will be conducted every 5–10 min based on the difference between predicted effluent coliform count and the control target.

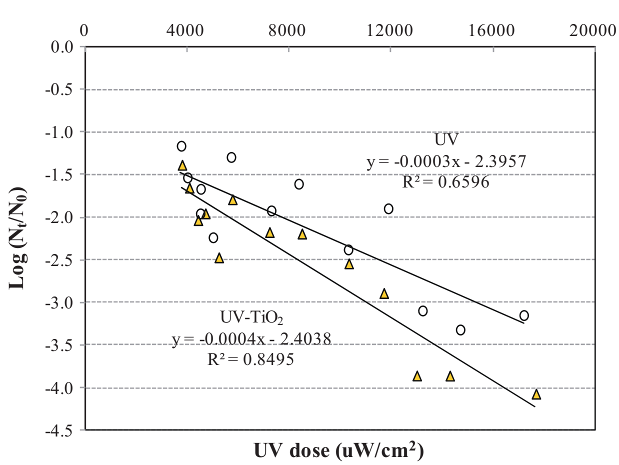

Fig. 4. Linear relationships between $\log(N_t/N_0)$ with UV dose for UV and UV-TiO_2 disinfections in this study.

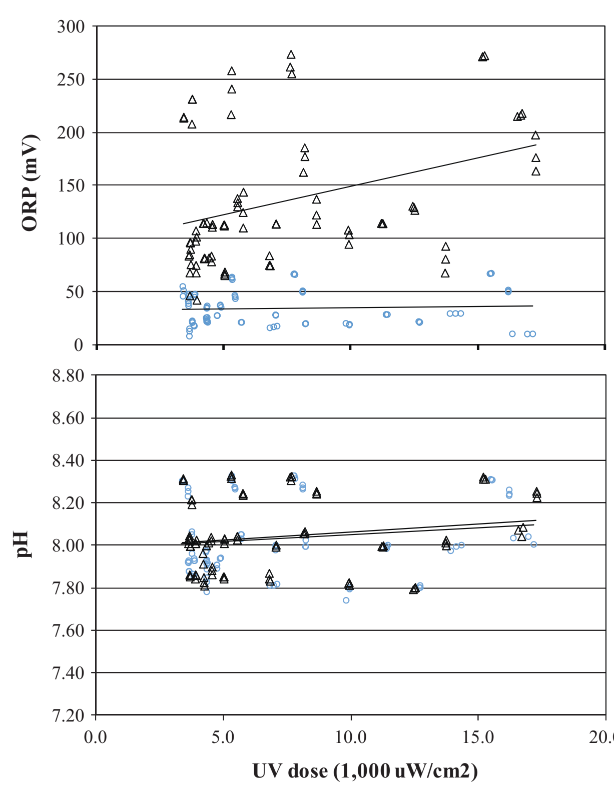

Fig. 5. Monitored ORP and pH values in the UV (○) and UV-TiO_2 (△) disinfection reactors.

Table 3
Details of the BPN control models in this study.

BPN model	Input parameter	Output parameter	R^2	Network architecture	Optimization algorithm				
					Train cycle	Random seed	Learn rate	Train RMS	Test RMS
For UV disinfection									
BPN_1	UV intensity, contact time, influent coliform counts, turbidity, color, ORP, pH, temperature	Effluent coliform counts	0.92	8-5-1	20, 000	0.31	4.0	0.042	0.047
For UV-TiO_2 disinfection									
BPN_2	UV intensity, contact time, influent coliform counts, turbidity, color, ORP, pH, temperature	Effluent coliform counts	0.95	8-6-1	25, 000	0.31	4.0	0.032	0.029

Where UV intensity (W/m^2), contact time (s), influent/effluent coliform counts (CFU/100 mL), turbidity (NTU), color (ADMI), ORP (mV), temperature (°C), pH.

3.4. Control verification for different wastewater reclamation proposes

Another series of UV and UV-TiO_2 disinfection experiments was conducted to evaluate the proposed BPN control strategy. The same real wastewater samples as in the previous experiments were used. Three control targets for total coliform counts were set based on three wastewater reuse purposes in Taiwan. Six experimental runs, three runs for UV disinfection and other three runs for UV-TiO_2 disinfection, were conducted to evaluate the proposed BPN-based control strategy. Each run was around 3–4 h. The control targets for total coliform counts were set as undetectable, 200, and 1000 CFU/100 mL. Table 4 shows the control targets, influent/effluent total coliform counts, and operational conditions of these six experimental runs.

The total coliform counts in influent were controlled at around 10^5 CFU/100 mL, which is close to total coliform counts in effluent after a second biological treatment in Taiwan. For wastewater reuse as sprinkle water and air-conditioner cooling water, undetectable total coliform counts are recommended. After BPN-controlled disinfection, total coliform counts in effluent were ND–25 CFU/100 mL (average, 10) and ND–15 CFU/100 mL (average, 8) for UV and UV-TiO_2 disinfection, respectively. In terms of coliform counts, both UV and UV-TiO_2 disinfection were effectively controlled. Compared with the required average UV dose of 12,290 μW s/cm^2 for UV disinfection, UV-TiO_2 disinfection required a lower average UV dose of 10,616 μW s/cm^2.

The recommended total coliform count is <200 CFU/100 mL when treated wastewater is reused for irrigation purposes. For this control target, the required average UV doses were controlled at 6415 μW s/cm^2 and 5409 μW s/cm^2 for UV and UV-TiO_2 disinfection, respectively. The total coliform counts in effluent under BPN control were 208–278 CFU/100 mL (average, 241) and 165–243 CFU/100 mL (average, 210) for UV and UV-TiO_2 disinfection, respectively. On the other hand, for wastewater reuse to flush toilets, the recommended total coliform count is <1000 CFU/100 mL. To meet this target, the BPN-controlled UV and UV-TiO_2 disinfection required average UV doses of 5525 μW s/cm^2 and 4794 μW s/cm^2, respectively. The controlled

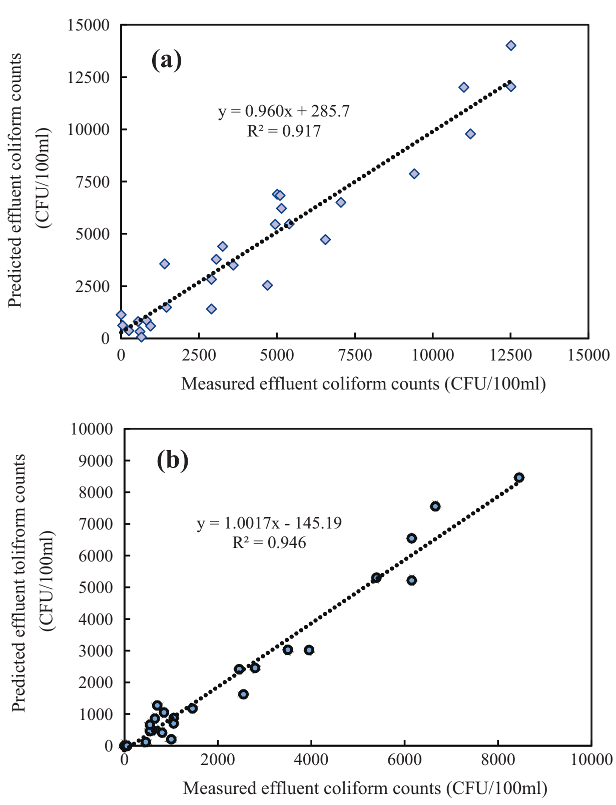

Fig. 6. Correlations between predicted and measured effluent coliform counts for (a) UV and (b) UV-TiO_2 disinfections by BPN models.

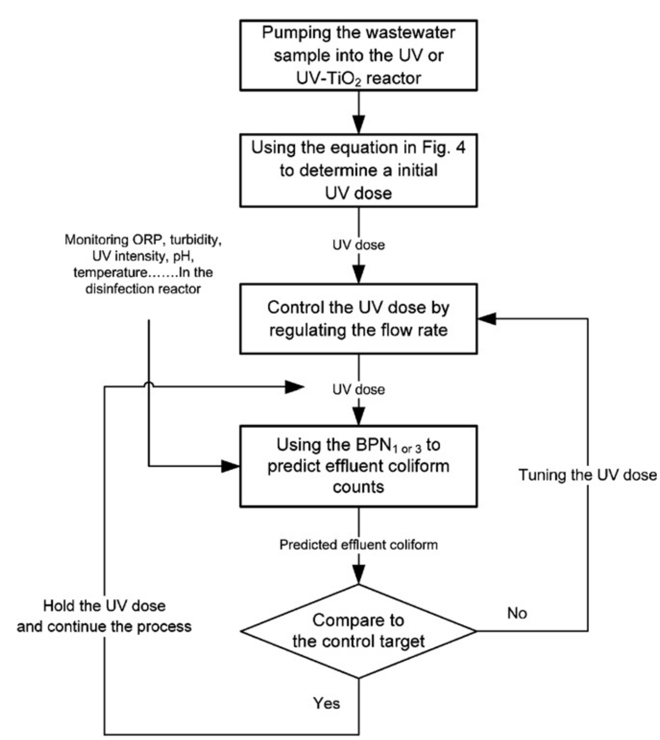

Fig. 7. Proposed BPN control strategy for UV and UV-TiO_2 disinfections in this study.

Table 4
Control results of UV and UV-TiO_2 disinfections for different wastewater reuse purposes using BPN control strategy.

Wastewater reclamation purpose	Average influent total coliform counts (CFU/100 mL)	Target for total coliform counts (CFU/100 mL)	Control effluent total coliform counts (CFU/100 mL)	Contact time (s)	UV dose ($\mu W\,s/cm^2$)
For UV disinfections					
Sprinkle water and air conditioner cooling	3.6×10^5	ND[a]	0–25 (10)[b]	80–93 (85)	10,110–13,428 (12,290)
Irrigation purpose	3.2×10^5	200	208–278 (241)	39–48 (45)	6101–6667 (6415)
Toilet flushing	3.0×10^5	1000	583–778 (695)	36–43 (40)	4861–6386 (5525)
For UV-TiO_2 disinfections					
Sprinkle water and air conditioner cooling	3.5×10^5	ND	0–15 (8)	72–80 (74)	9528–12,687 (10,616)
Irrigation purpose	3.9×10^5	200	165–243 (210)	37–44 (39)	5242–6080 (5409)
Toilet flushing	3.1×10^5	1000	540–658 (598)	32–38 (34)	4431–5504 (4794)

[a] ND means undetectable.
[b] ( ) means the average.

total coliform counts were 583–778 CFU/100 mL (average, 695) and 540–658 CFU/100 mL (average, 598) for UV and UV-TiO_2 disinfection, respectively. Both control results are within acceptable ranges.

Consequently, the proposed BPN control strategy effectively controls both UV and UV-TiO_2 disinfection, resulting in acceptable total coliform counts in effluent for three different wastewater reuse purposes. The required UV doses for UV-TiO_2 disinfection were lower than those for UV disinfection only, resulting in UV dosage saving and capacity reduction of 13.2–15.7%.

4. Conclusions

As UV and UV-TiO_2 disinfection are complex bio-chemical and physical phenomena, building a precise control model using typical mathematic models is extremely difficult and may be impossible. This study presents the application of BPN models with multiple parameters to control UV and UV-TiO_2 disinfection. Experimental results demonstrate that BPN models can correlate precisely the relationships among multiple monitored parameters, and can be used as control models for both UV and UV-TiO_2 disinfection. The proposed control strategy using BPN models effectively controls the UV and UV-TiO_2 disinfection processes to meet the recommended total coliform counts in effluent for three different wastewater reuse purposes. For the wastewater reclamation proposes of conditioner cooling, irrigation and toilet flushing, the required UV doses were around 12,290 $\mu W\,s/cm^2$, 6415 $\mu W\,s/cm^2$, and 5525 $\mu W\,s/cm^2$ for UV disinfection, and 10,616 $\mu W\,s/cm^2$, 5409 $\mu W\,s/cm^2$, and 4794 $\mu W\,s/cm^2$ for UV-TiO_2 disinfection, respectively. Experimental results demonstrate the potential benefits of process effectiveness and operational cost savings for both UV and UV-TiO_2 disinfection.

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