Disinfection and oxidation of sewage effluent water using ozone and UV technologies


Department of Environmental Engineering, YIEST, Yonsei University, 234 Maeji, Heungup, Wonju city, Kangwon, South Korea (E-mail: jwk@yonsei.ac.kr)

Abstract This study was aimed at exploring the reclamation of sewage treatment plant effluent water (SEW) as an alternative water resource. For the oxidation of SEW, an ozone-UV system, based on the results of the combined ozone/UV process performed in our previous study, was set up under practical conditions, including a series type, continuous mode, semi-pilot scale operation (1.5 m³/d). As a result, the serial contact of the ozone and UV reactors showed lower CODCr and TOC removal efficiencies. However, these were greatly enhanced by recycling the water flow of the ozone-UV system at 40Q, as a result of the improvements in the transferred ozone dose in the ozone reactor and the contact efficiency between photons and ozone in the UV reactor, which approached that achieved in the combined ozone/UV process.

For the disinfection of SEW, carried out in a syringe-type batch reactor, the increase of instantaneous ozone demand (ozone ID) led to a higher inactivation efficiency, an increased UV transmittance due to ozonation, and an enhanced inactivation rate of E. coli in the UV reactor. Additionally, it was concluded that the ozone/UV process could overcome the limitations of the ozone alone and UV alone processes for the reclamation of sewage effluent water.

Keywords Ozone; ozone-UV; reclamation; sewage effluent water; UV

Introduction

Recently, numerous studies have been conducted on the reclamation of sewage treatment plant effluent water (SEW) to find a solution to the water shortage problem (Tyrrell et al., 1995; Wethern and Katsaras, 1995; Shon et al., 2004). In Korea, which faces a 1.8 billion tons water shortage by 2011, much effort has been made to reuse the 6.7 billion tons of SEW produced per year. As part of these endeavours, in our previous study (Oh et al., 2004) the combined ozone/UV process in a semi-batch mode was evaluated and compared with the ozone alone and UV alone processes. The ozone/UV process showed excellent efficiency for the mineralisation of organics (90% removal of TOC with 8 W/L UV lamp and 300 mg/L ozone dose) and the minimisation of ozone by-products (50% reduction of aldehydes with an 8 W/L UV lamp and 80 mg/L ozone dose), overcoming the oxidative limitation of the ozone alone process. From this, it could be concluded that hydroxyl radicals (·OH) played a major role in the elimination of the organics present in the SEW. The ozone alone process was sufficient for colour removal only, and both ozone alone and UV alone were effective for the inactivation of E. coli. In this study, a series type ozone-UV system was set up for simple application in sewage treatment plants, in which mostly the ozone or UV process was applied, as a single unit, and evaluated on the enhancement of the oxidative efficiency for the reuse of SEW. Also, the system was evaluated as a pre-step for use in a practical plant. With regard to disinfection, the SEW usually has different water characteristics from those of other water sources, such as river, reservoir and ground water (Shon et al., 2004). Especially, due to the (in)organic constituent, the SEW requires a relatively high disinfectant demand (i.e. chlorine, ozone and UV etc.). However, there have been few studies in the field of SEW...
reclamation. Therefore, in this study, a laboratory scale test was additionally performed in order to investigate the effect of the instantaneous ozone demand (ozone ID), UV transmittance and (in)organic constituents of SEW on the microbial inactivation as a specific observation.

**Methods**

As the target sample water, sewage treatment plant effluent water (SEW) was collected from a sewage treatment plant at Yonsei University in Wonju city. The characteristics of the test water were as follows: COD$_{Cr}$, 22–30 mg/L; BOD$_5$, 5–8 mg/L; TOC, 8–11 mg/L; UV$_{254}$, 0.12–0.17 cm$^{-1}$; UV$_{410}$, 0.015–0.017 cm$^{-1}$; Water Temperature, 10–15$^\circ$C; pH, 6.2–6.8; alkalinity, 15–25 mg/L as CaCO$_3$. For the oxidation of SEW, a series type ozone-UV system was set-up, equipped with an 8-L UV reactor and a 20-L ozone contactor, as shown in Figure 1. A low-pressure Hg arc lamp (WEDECO, Germany), with an 8 W/L UV intensity, was used as the UV source, and gaseous ozone (2 mg/L – 60 mg/L) was diffused into the contactor via an ozone generator (OZONIA, USA). The COD$_{Cr}$, TOC and UV absorbance at 410 nm (as a parameter of organics containing colour, UV$_{410}$) and 254 nm (as a parameter of refractory organics containing ring structure, UV$_{254}$) were used as the targeted organic parameters. Each experiment for the removal of the organics present in SEW was performed in a continuous mode (1.5 m$^3$/day), with various ozone doses, and each data point was obtained from the average of 10 samples collected every hour during the day. In order to raise the oxidative efficiency in the ozone-UV system, the water flow was recycled from the outlet of UV reactor to the inlet of the ozone contactor, with a recycling ratio of 40Q. This ratio was established for the fast circulation only. The residual ozone concentrations in the samples were continuously measured by flow injection analysis (FIA) using the Indigo method (Hoigne and Bader, 1981). As measures of the disinfection, the inactivation of *E. coli* and *P. aeruginosa* were investigated in a syringe-type reactor (50 mL) in both the batch and semi-batch modes, respectively. The analysis of bacteria was performed using the plate counting method. The initial number of cells in the sample for the disinfection was controlled at approximately 10$^5$ CFU/mL.

**Results and discussion**

**Oxidation of SEW**

For the removal of the organics present in the SEW, the ozone alone and ozone/UV processes were compared in a series type ozone-UV system, using several parameters,
such as UV absorbing organics (UV$_{410}$, UV$_{254}$), COD$_C$, and TOC. The recycling effect on the oxidative efficiency of the ozone-UV system was the main parameter investigated. Also, since the UV alone process showed no oxidative action, the data from the UV alone process have been omitted from Figures 2 and 3. In Figure 2(a), the ozone alone and ozone-UV processes showed almost same UV$_{410}$ removal efficiency regardless of recycling ratio, indicating that the organics responsible for the colour could easily be eliminated by either molecular ozone or (OH. In the case of the UV$_{254}$, as shown in Figure 2(b), the ozone-UV process showed greater removal efficiency than that of ozone alone; recycling the system also led to a larger gap between the processes, yielding 40 and 70% removals of the UV$_{254}$ in the ozone alone and ozone-UV processes with recycling, respectively. This result indicates that recycling was more favourable in the ozone-UV than the ozone alone process. The optimum ozone doses for the UV$_{410}$ and UV$_{254}$ removals were found to be approximately 20 and 10 mg/L, respectively.

In Figure 3(a), the ozone-UV process showed a higher COD$_C$ removal efficiency than the ozone alone process with ozone doses less than 10 mg/L, but the pattern of COD$_C$ removal of both processes were similar at higher ozone doses. Meanwhile, for the TOC, as shown in Figure 3(b), although the removal efficiency in the ozone-UV was higher than that in the ozone alone process, the maximum removal efficiency was only 25%. Conversely, with the ozone-UV system recycled at a ratio of 40Q, the efficiency of the ozone-UV process was significantly enhanced compared to that of the ozone alone process for both COD$_C$ and TOC, with removal efficiencies of 80 and 60%, respectively.

The enhanced removal efficiencies as shown in Figures 2 and 3 might be attributable to the improvements in the transferred ozone dose in the ozone reactor and the contact efficiency between photons and ozone in the UV reactor, which approached that in the combined ozone/UV process. This presumption could be supported by the residual ozone concentrations measured in the ozone alone and ozone-UV processes, both with and without recycling, as shown in Figure 4. The residual ozone concentration in the sample from the ozone contactor was greatly increased by recycling the system. However, regardless of recycling, no residual ozone was detected after UV irradiation. This result implies that a set-up arranged for the greater ozone transfer followed by UV irradiation might be a recommended method for the SEW oxidation since it is able to lead to a greater amount of -OH formation. In fact, the serial connection of the ozone and UV reactors was not effective for the elimination of the refractory organics, due to the high ozone demand in the ozone contactor; conversely, the combined ozone/UV process might be better for the oxidation of SEW, which can occur due to the reaction between ozone and photon as soon as gaseous ozone is transferred into the liquid phase. Therefore, if the series type
ozone-UV system is set up for the SEW treatment; it can be proposed that the system should be properly modified to the target treatment objectives (e.g. disinfection or oxidation).

Table 1 compares the removal efficiencies of organics by the ozone alone, the UV alone, the ozone/UV process from both in the lab-scale experiment in our previous study (Oh et al., 2004) and the semi-pilot scale experiment of the ozone alone, the UV alone and the ozone-UV in series with recycling in this study. In the semi-pilot reactor system, the UV dose was fixed at 64 W-min/L using a high intensity Hg-arc (typical emitted wavelength is 254 nm) with a fixed UV irradiation time (8 min) whereas the variable UV doses (4-1200 W-min/L) were applied in the lab-scale reactor system. Organic parameters such as UV410, UV254, CODCr and TOC were used as probes to evaluate their oxidation performances. The percentage removals of UV410 with the ozone alone process were 85 and 80% with 16 and 20 mg/L of ozone dose in the lab-scale and the pilot-scale operation, respectively. The percentage removals of UV254 with the ozone alone process were 50% in the lab-scale and 35% in the semi-pilot in the semi-scale reactor system. The lower removal rate in the semi-pilot system is due to the inefficient ozone mass transfer in the ozone gas diffusing type of bubble column (1 m height) reactor installed in the semi-pilot system. The typical ozone utilization in this contactor was only 50%, and improved to 65% when the system was operated with recycle mode. The poor ozone mass transfer efficiency found in the semi-pilot system suggests some alternative ozone
contacting device like ozone injector system for the ozone-UV in series operation. As compared to the ozone alone or UV alone, the ozone/UV or the ozone-UV in series showed an increased removal rate of UV254, CODCr and TOC both in the lab-scale and the semi-pilot scale system. The percentage removal of CODCr was increased from 60 to 90% in the lab-scale and 55 to 80% in the pilot-scale system combing ozone with UV irradiation. For the case of TOC elimination, the ozone/UV process or the ozone-UV in series operation showed the best performance, however, significant amount oxidants are required to achieve complete mineralisation.

Disinfection of SEW
In general, the inactivation of microbial is totally dependant on the CT value (product of disinfectant concentration and exposure time) of the disinfectant (Federal Register, 1989). However, since the SEW has a high ozone demand, especially instantaneous ozone demand (ozone ID) (Oh et al., 2004), the CT rule cannot be applied for the case of SEW disinfection. Thus, in this study, the effect of the ozone ID on SEW disinfection was investigated. Figure 5 shows the inactivation efficiencies of E. coli as a function of the ozone ID values. In Figure 5(a), the residual ozone in the SEW was detected at various initial ozone doses; 0.3, 0.6, 1.1 and 1.9 mg/L. With initial ozone doses of 0.3 and

![Image](https://iwaponline.com/wst/article-pdf/55/1-2/299/430962/299.pdf)
0.6 mg/L, the ozone was completely decomposed as soon as it was injected. With ozone doses of 1.1 and 1.9 mg/L, the ozone instantaneously decayed by 0.1 and 0.6 mg/L, yielding ozone IDs of 1.0 and 1.3 mg/L, respectively. The values of the ozone ID were linearly increased with increasing initial ozone dose (Figure 5(b)). In particular, the inactivation of *E. coli* occurred during the ozone ID phase, and showed a linear relationship. At an initial ozone dose of 1.1 mg/L, a *CT* value of 0.008 mg-min/L was observed to be able to inactivate 0.4 log (Cho et al., 2004), but the *E. coli* was inactivated by 1.2 log (not present in this figure), including 0.9 log removal in the ozone ID phase. In this study, the development of a control parameter for the prediction of the ozone disinfection efficiency due to ozonation of SEW still remains. However, for the SEW disinfection, this result clearly indicates that the ozone ID parameter is strongly recommended to use as one of the key control parameters along with the parameter of ozone *CT* value.

In the oxidation of SEW, as mentioned previously, the ozone could effectively reduce the UV absorbing organics (Figure 2). This directly indicates the enhancement of UV transmittance. In this study, in order to investigate the effect of transmittance on SEW disinfection, the *E. coli* inactivation due to UV irradiation was performed with three samples having different transmittances, as follows: raw water of SEW, transmittance = 62%; SEW ozonated with 10 mg/L ozone, 80%; and organic-free water (DW), 100%, with the results shown in Figure 6. At every transmittance, the inactivation efficiencies were increased with increasing UV irradiation time, and were highest in DW. Especially, the inactivation efficiency in the ozonated sample was enhanced by 3 log compared to the SEW, with 2 log reduction at irradiation time of 60 sec. The inserted plot in Figure 6 shows an extremely linear relationship between the transmittance and a pseudo first-order rate constant (*k_o*) for *E. coli* inactivation. This result demonstrated that the increase in UV transmittance due to ozonation of the SEW directly led to the enhancement of the disinfection efficiency. From an economic point of view, the cost of the UV alone process with 62% transmittance was 116 Won/m³, but the ozone-UV series process with 80% transmittance, which can be achieved with a 10 mg/L or pre-ozonation, can save approximately 20 Won/m³. Some may argue that since an ozone dose of 10 mg/L can possibly inactivate almost all bacteria disregarding improvement of the UV transmittance, the UV process might be inevitable when our target objectives are to kill ozone-resistant microorganisms which might be present in SEW.

Inactivation of *P. aeruginosa*, which is always present in sewage effluent, was investigated. Experiments were performed in both deionised water (DW) and SEW.

![Figure 6](https://iwaponline.com/wst/article-pdf/55/1-2/299/430962/299.pdf)
spiked with *P. aeruginosa* for kinetic study. Figure 7 shows the pseudo first-order rate plots for *P. aeruginosa* elimination due to the ozone alone, UV alone and combined ozone/UV processes. Table 2 summarises the inactivation rate constants for *P. aeruginosa* by each process. The highest inactivation rate constants for both target water samples were found with the ozone/UV process, showing significant enhancement of *P. aeruginosa* elimination compared to the sum of the efficiencies of the ozone and UV alone processes. The values calculated by $k_{O3/UV} = (k_{O3} + k_{UV})$ indicate an enhanced ratio by the combining of ozone and UV, and were to be 1.70 (70% enhancement) and 3.28 (228% enhancement) in the DW and SEW, respectively. Meanwhile, the values presented for $E_{constituents}$ indicate a change in the ratio of the inactivation rates, due to the different constituents of the DW and SEW. The order of the $E_{constituents}$ values was as follows: ozone alone > UV alone > ozone/UV. This implies that the ozone/UV process could overcome the limitations in the ozone alone and UV alone processes. In order to explain the significant gap between the ozone alone and ozone/UV processes, the mechanism of the ozone process should be elucidated. According to (Staehelin and Hoigné, 1982), the mechanism of the reaction of ozone with the substances in water can be divided into two distinct pathways. The first route is the direct attack of molecular ozone; and the second, the indirect reaction of ·OH formed by ozone decomposition. In the case of the ozone/UV process, molecular ozone is quickly decayed by UV irradiation, and then converted to ·OH. Therefore, considering the $E_{constituents}$ values, it can be concluded that direct reaction of molecular ozone, rather than that of ·OH and photons, is most easily affected by the constituents in the waters. Also, the enhanced efficiency of the ozone/UV process could have resulted from the abundant formation of ·OH, which has been supported by several researchers (Sjogren and Sierka, 1994; Watts *et al.*, 1995; Bekbolet, 1997), who demonstrated that ·OH can play an important role in the photocatalytic bactericidal action.

![Figure 7](https://iwaponline.com/wst/article-pdf/55/1-2/299/430962/299.pdf)

**Figure 7** Inactivation of *P. aeruginosa* by ozone, UV and ozone/UV processes, ozone dose = 0.8 mg/L-min, UV dose rate = 0.4 W/L

<table>
<thead>
<tr>
<th></th>
<th>$k_{O3}$ (min$^{-1}$)</th>
<th>$k_{UV}$ (min$^{-1}$)</th>
<th>$k_{O3/UV}$ (min$^{-1}$)</th>
<th>$k_{O3/UV} = (k_{O3} + k_{UV})$</th>
<th>$E_{constituents}$</th>
<th>$E_{constituents}$ = Effect of constituents between DW and SEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic-free water (DW)</td>
<td>0.304</td>
<td>2.219</td>
<td>4.287</td>
<td>1.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEW</td>
<td>0.075</td>
<td>1.058</td>
<td>3.711</td>
<td>3.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{O3/UV}/k_{SEW}$ (Econstituents)$^b$</td>
<td>4.04</td>
<td>2.09</td>
<td>1.16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Enhancement of the inactivation efficiency due to ozone/UV compared to the sum of the efficiencies of the ozone alone and UV alone processes

$^b$ Effect of constituents between DW and SEW
Conclusions
For the reclamation of sewage treatment plant effluent water (SEW), the oxidation and disinfection efficiencies of ozone and UV were investigated. The ozone-UV process of the tested processes showed the highest efficiency for removing the organics in SEW, and the oxidative efficiency of the series type ozone-UV system could be enhanced by recycling. This was due to the improvements in the transferred ozone dose in the ozone reactor and the contact efficiency between photons and ozone in the UV reactor. For SEW disinfection, the E. coli could be inactivated during the ozone ID phase, which showed a linear relationship between the inactivation rate and ozone ID concentration. For the proper disinfection of SEW, both of the ozone ID value and ozone CT value are to be recommended for use as control parameters. The UV transmittance in SEW was increased by the pre-ozonation with only small ozone dosage, and led to an enhanced inactivation of E. coli. The inactivation efficiencies of the ozone, UV and ozone/UV processes were compared using P. aeruginosa as a probe. This result demonstrated that the ozone/UV process could overcome some drawbacks of the ozone alone process and UV alone process since its application is very limited according to the constituents of the SEW.

Acknowledgements
This work was supported by grant No.(R01-2002-000-00313-0) from the Basic Research program of the Korea Science & Engineering Foundation.

References