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Comparative Study of Disinfection of Secondary Treated Wastewater Using Chlorine, UV and Ozone

1Abou-Elela S.I., 2El-Sayed M.M.H., 3El-Gendy, A.S., 4Abou-Taleb E.M.

1,4Water Pollution Research Department, National Research Center, Cairo, Egypt.
2Chemical Engineering and Pilot Plant Department, National Research Center, Cairo, Egypt; also affiliated to Chemistry Department, American University in Cairo, Egypt. AUC Avenue, New Cairo, Egypt.
3Department of Environmental Engineering, Institute of Environmental Studies and Research, Ain Shams University, Cairo, Egypt.

ABSTRACT

In this study, evaluation of the efficiency and viability of using chlorine, UV irradiation, and ozone as disinfectants for secondary treated wastewater was investigated. Complete inactivation of total coliform, fecal coliform, Pseudomonas, and Staphylococcus was achieved using 32 mg/L chlorine after 15 min. Disinfection by 15 mg/L of ozone for 15 min completely removed all the investigated pathogens. In addition, the use of a low pressure UV dose (164 mWs/cm2) reduced the Total Coliform Count (TCC) by 3 logs, while complete removal of Fecal Coliform Count (FCC), Pseudomonas and Staph was attained. Economic analysis of each disinfection process revealed that chlorination is the most economical process followed by UV irradiation then ozonation. However, residual chlorine, even at low concentration is toxic to aquatic life thus dechlorination would be necessary. Furthermore, all forms of chlorine are highly corrosive and toxic thus storage, shipping and handling pose safety risks. Therefore in view of the technical, financial and environmental merits, ultraviolet (UV) irradiation is recommended as the safest and most economical option among the three investigated disinfectants.

Key words: disinfection, chlorination, UV irradiation, ozonation, techno-economic study, secondary treated wastewater.

Introduction

Untreated and secondary treated wastewater effluents contain a wide range of pathogenic micro-organisms that pose a potential risk to the health of humans and livestock. Therefore, disinfection is mandatory for the removal of these pathogens in order to prevent the spread of waterborne diseases to downstream users and the environment. The three most common methods of disinfection are chlorination, ozonation, and ultraviolet (UV) irradiation (Macauley et al. 2006).

Conventional disinfection of wastewater by the chlorination method was adopted by a number of workers. For the disinfection of sewage treated with activated sludge and filtration, Blanken (1985) applied 3.65 mg/L sodium hypochlorite for 25 min, whereas Veschetti et al. (2003) employed the same disinfectant at doses ranging from 0.5 to 4.0 mg/L and contact times of 8 to 38 min. Furthermore, Macauley et al. (2006) used sodium hypochlorite for disinfection of swine wastewater. Applied doses ranged from 5 to 500 mg/L and contact time was 2.5 h. A 2.2-3.4 log bacteria reduction was achieved using a 30 mg/L chlorine dose.

Relatively recent disinfection alternatives include UV irradiation and ozonation. For the former, Amin et al. (2010) disinfected secondary municipal wastewater effluent on a pilot-scale using low-pressure and medium pressure UV lamps. Lindenauger and Darby (1994) examined the different parameters affecting the photo reactivation of total coliform for UV disinfection of secondary effluent, and found UV dose to be the most significant. Naddeo et al. (2009) investigated the disinfection of municipal wastewater using a UV reactor where they studied the effect of reaction time and UV dose. In addition, Caretti and Lubello (2003) performed a pilot plant study to validate the disinfection efficacy of the synergic combined treatment of UV and peracetic acid. Samples were subjected to a UV dose of 100-300 mWs/cm2 and a peracetic acid dose of 2-8 ppm for a period of 10-30 min.

Regarding ozonation, Macauley et al. (2006) applied an ozone dose of 100 mg/L to swine wastewater and achieved bacteria inactivation efficiency of 3.3—3.9 log bacteria. Silva et al. (2010) ozonized anaerobic sanitary wastewater effluent with ozone doses of 5, 8 and 10 mg/L for time periods of 5, 10, and 15 min, whereas Blanken (1984) subjected treated sewage to 15.3 mg/L ozone for 25 min. In addition, wastewater effluents from...
secondary and tertiary treatments were disinfected by ozone doses of 3-50 mg/L at respective contact times of 2-10 min and with doses of 1-35 mg/L at contact times of 3-15 min (Xu et al. 2002).

The aim of this study is to evaluate the efficacy and viability of using chlorine, ozone and ultraviolet irradiation for the disinfection of a secondary treated wastewater effluent obtained from a pilot-scale treatment system comprising anaerobic treatment, high rate settling and multistage sand filtration. The most suitable disinfection process will be recommended based on analyses of the technical and economic aspects of each disinfection process.

Methods:

A pilot-scale treatment system was constructed and tested for wastewater treatment at Abo-Rawash wastewater treatment plant in Giza, Egypt. The pilot scale setup (Figure 1) consisted of a Packed Up-Flow Anaerobic Sludge Blanket (P-UASB), followed by a high rate Inclined Plate Settler (IPS) and finally a Multi-Stage Roughing Sand Filter (MSRSF) (Abou-Elela et al., 2011). Raw wastewater is pumped as an influent to the treatment system after screening and grit removal. Samples of the treated effluent from this system were collected for studying the performance of different disinfection processes; namely, chlorination, ultraviolet (UV) irradiation and ozonation. After disinfection, the samples were analyzed for total coliform, fecal coliform, Pseudomonas and Staphylococcus counts. The details of each disinfection process are given below.

Chlorination:

Chlorine was added to samples collected from the effluent of the treatment system (Figure 1) at doses ranging from 2 to 41 mg/L chlorine water. The optimum chlorine dose (i.e. the chlorine breakpoint) was determined from a breakpoint curve. The concentration of residual chlorine was calculated for the different chlorine doses according to the procedures outlined in the ‘Standard Methods for Water and Wastewater’ (APHA 2005). The effluent from the treatment system was subjected to the optimum chlorine dose for a contact time of 15 min. The disinfected sample was analyzed for total coliform, fecal coliform, Pseudomonas and Staphylococcus counts.

UV Irradiation:

Samples from the pilot-scale treated effluent were subjected to a UV irradiation using a low-pressure mercury lamp. The lamp generates UV light with wavelength ranging between 250 nm and 270 nm. This lamp was located above the reaction vessel, which is a glass vessel with a volume of 500 mL. In order to determine the optimum contact time, samples were subjected to UV irradiation at different time intervals (5-20 min). The UV dose per unit area was then calculated using the following equation:

\[ d_{UV} = t \times I \]  

where

- \( d_{UV} \) = UV dose in mWs/cm²
- \( t \) = time of UV exposure in seconds
- \( I \) = intensity of UV light in mW/cm²

Fig. 1: Schematic diagram of the pilot-scale treatment system.
Ozonation:

Samples of 200 mL each, from the pilot-scale treated effluent, were ozonized using an ozonizer (Ozone Lab, D-6900 Hydelberg-prominence, Germany). The ozone dose was calculated using the following equation:

\[
d_{\text{ozone}} = \frac{(r \times t \times 1000)}{V}
\]

where

- \(d_{\text{ozone}}\) = ozone dose in mg/L
- \(r\) = rate of ozonation in mg/min
- \(t\) = time of ozonation in min
- \(V\) = volume of sample in liter

The optimum ozone dose was initially determined by the addition of doses ranged from 2 to 15 mg/L into the collected samples from the effluent of the pilot-scale treatment system. At the optimum ozone dose, samples from the effluent of the pilot-scale treatment system were disinfected with ozone at different contact times (2 to 15 min).

Determination of bacterial counts:

Ten fold serial dilution of each sample was prepared in sterile saline till the bacterial count is in the order of \(10^7\). A 100 µL of each dilution was streaked on each of the following agar plates: EMB agar, m-FC agar, Cetramide agar and Mannitol salt agar media for the detection of TCC (total coliform count), FCC (fecal coliform count), Pseudomonas count and Staphylococcus count, respectively. After inoculation of samples, m-FC plates were incubated at 44°C/24 h for monitoring of fecal coliform counts, while other plates were incubated at 37°C/24 h for monitoring of total coliform counts, Pseudomonas and Staph counts. All equipment was sterilized before use.

Results and Discussion

Characterization of the treated effluent before disinfection:

Table 1 shows the average values for the physico-chemical characteristics as well as the pathogenic analyses of the raw and treated wastewater. The results depicted in this table show that the treatment system (Figure 1) substantially removed most of the pathogens as indicated by the values of the total coliform and fecal coliform counts. However, disinfection is still required to ensure a safer quality of the effluent prior to its reuse. The results of disinfection using the three methods under investigation are as follows.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Raw Wastewater(^1)</th>
<th>Treated Effluent(^2)</th>
<th>% Removal</th>
<th>Limits of the ECP 501-2005(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.8-7.5</td>
<td>7.0</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>200.0</td>
<td>10.9</td>
<td>94.50</td>
<td>20.0</td>
</tr>
<tr>
<td>COD (mg O₂/L)</td>
<td>320.0</td>
<td>60.3</td>
<td>81.50</td>
<td>20.0</td>
</tr>
<tr>
<td>BOD (mg O₂/L)</td>
<td>190.0</td>
<td>34.6</td>
<td>81.8</td>
<td>60.0</td>
</tr>
<tr>
<td>Total coliform (MPN/100 mL)</td>
<td>2.8×10(^7)</td>
<td>1.1×10(^5)</td>
<td>99.99</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Fecal coliform (MPN/100 mL)</td>
<td>1.5×10(^7)</td>
<td>2.8×10(^4)</td>
<td>99.99</td>
<td>&lt;5000</td>
</tr>
<tr>
<td>Pseudomonas (MPN/100 mL)</td>
<td>7.0×10(^8)</td>
<td>70.0</td>
<td>99.99</td>
<td>...</td>
</tr>
<tr>
<td>Staphylococcus (MPN/100 mL)</td>
<td>5.0×10(^7)</td>
<td>90.0</td>
<td>99.99</td>
<td>...</td>
</tr>
</tbody>
</table>

\(^1\)Average of 25 samples
\(^2\)Effluent from the pilot-scale treatment system shown in Figure 1
\(^3\)ECP = Egyptian Code of Practice for the use of treated wastewater in agriculture

Chlorination:

The optimum chlorine dose was determined from the chlorine breakpoint curve and was found to be 32 mg/L with a contact time of 15 min. The different bacterial counts obtained before and after disinfection at the pre-determined chlorine dose are given in Table 2. Exposure of treated effluent to the optimum chlorine dose was capable of reducing TCC from \((1.1×10^5)\) to \((2×10^3)\) and was capable of complete hindrance of fecal coliform (FC) (Table 2). Almost 99.98% removal of total coliform (TC) was obtained at the optimum dose, a percentage that exceeds the one imposed by the National Environmental Legislations. The high removal of fecal coliform with chlorination could be attributed to the change in the permeability of the micro-organism cell membrane or to the impaired enzymatic activity of the microorganism (Venkobachar et al., 1977; Roller, 1980; Straub et al., 1995, Francy et al., 2012).
Table 2: TCC, FCC, Pseudomonas and Staph counts before and after chlorination at optimum chlorine dose (32 mg/L) and optimum contact time (15 min).

<table>
<thead>
<tr>
<th>Parameters (MPN/100 mL)</th>
<th>Before disinfection</th>
<th>After disinfection</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCC</td>
<td>$1.1 \times 10^3$</td>
<td>$2 \times 10^1$</td>
</tr>
<tr>
<td>FCC</td>
<td>$2.8 \times 10^2$</td>
<td>-ve</td>
</tr>
<tr>
<td>Pseudomonas</td>
<td>70</td>
<td>-ve</td>
</tr>
<tr>
<td>Staph</td>
<td>85</td>
<td>-ve</td>
</tr>
</tbody>
</table>

UV irradiation:

The effect of UV irradiation on the disinfection of the treated effluent of the pilot-scale system was studied at different exposure time intervals of 1, 3, 5, 7, 10, 15 and 25 min. The effluents samples, before and after disinfection, were tested for TCC, FCC, Pseudomonas, and Staphylococcus counts.

Figure 2 shows the inactivation of the total coliform and fecal coliform with the exposure time to UV irradiation. The inactivation is expressed as a ratio of the TCC or FCC in the disinfected samples at time $t$ ($N_t$) to the initial counts prior to disinfection ($N_{t0}$).

![Fig. 2: Comparison between the time courses for the total coliform and the fecal coliform inactivation using UV irradiation.](image)

The figure shows that both the TCC and FCC decrease exponentially with time and hence inactivation increases. The inactivation of TC or FC at time $t$ can thus be represented by Equation 3.

$$\frac{N_t}{N_{t0}} = e^{-kt}$$  \hspace{1cm} (3)

where “$k$” is the inactivation rate constant which depends on the type of organism, and the UV dose. The inactivation rate of TC or FC using UV irradiation can then be correlated with time using Equation 4.

$$\frac{d}{dt} \left( \frac{N_t}{N_{t0}} \right) = -k \left( \frac{N_t}{N_{t0}} \right)$$  \hspace{1cm} (4)

It can also be deduced from the figure that the rate of inactivation was higher for the total coliform than that for the fecal coliform, as indicated by the higher value of the inactivation rate constant for total coliform ($k_{TCC} = 0.707$ min$^{-1}$) as compared with fecal coliform ($k_{FCC} = 0.406$ min$^{-1}$).

Furthermore, exposure of the treated effluent to a UV dose (164.1 mWs/cm$^2$) was capable of reducing TCC by 3 logs after an exposure time of 10 min, as well as reducing FCC by 2 logs after an exposure time of 15 min. In addition, UV irradiation completely inactivated the Pseudomonas and Staphylococcus in the treated effluent within 15 min of exposure. Therefore, 15 min is recommended as the minimum exposure time to UV irradiation for the effluent disinfected at a UV dose of 164.1 mWs/cm$^2$. 
Ozonation:

To investigate the performance of ozonation, samples from the treated effluent of the pilot scale system were collected and exposed to ozone at different doses ranging from 2 to 15 mg/L and at a contact time of 15 min. Figure 3 shows the change in the inactivation of TC and FC, expressed as \((N_t/N_{to})\), as a function of ozone dose. As shown in the figure, the optimum dose at which complete disinfection occurred was found to be 15 mg/L.

![Inactivation time courses for total and fecal coliforms under different doses of ozone treatment and a contact time of 15 min.](image1)

Fig. 3: Inactivation time courses for total and fecal coliforms under different doses of ozone treatment and a contact time of 15 min.

Another set of ozone treatment experiments were carried out at the pre-determined optimum ozone dose and at different time intervals ranging from 2 to 15 min. Figure 4 depicts the change in the inactivation of TC and FC, expressed as \((N_t/N_{to})\), with the ozone contact time at an ozone dose of 15 mg/L.

![Inactivation time courses for total and fecal coliforms under ozone treatment at an optimum dose of 15 mg/L and different contact times.](image2)

Fig. 4: Inactivation time courses for total and fecal coliforms under ozone treatment at an optimum dose of 15 mg/L and different contact times.

It is clear from the figure that the inactivation rate of TC or FC at time \(t\) can be described by Equations 3 and 4 with values of the rate constant different from those pertaining to the UV treatment. As shown in the figure, a higher rate of inactivation was obtained for fecal coliform as compared to total coliform using ozone.
disinfection. This can also be concluded from the higher value of inactivation rate constant for fecal coliform ($k_{FCC} = 0.338 \text{ min}^{-1}$) as opposed to total coliform ($k_{TCC} = 0.225 \text{ min}^{-1}$).

It can also be inferred from the figure that almost complete hindering of total coliform and fecal coliform was achieved by the addition of 15 mg/L ozone dose with a contact time of 15 min. Furthermore, an ozone dose of 15 mg/L was capable of complete inactivation of Pseudomonas and Staphylococcus in the treated effluent within 2 min of contact time. Therefore, it can be concluded that complete disinfection using ozone can be achieved with the addition of 15 mg ozone/L for 15 min of contact time.

Comparison of the different disinfection processes:

Comparison between the inactivation courses for the TCC and FCC under the optimum UV and ozone disinfection conditions is shown in Figure 5.

![Comparison between the performance of UV and ozone treatment in the inactivation of total coliform and fecal coliform.](image)

**Fig. 5:** Comparison between the performance of UV and ozone treatment in the inactivation of total coliform and fecal coliform.

From this figure and as discussed previously, it can be concluded that the rate of inactivation for both the TC and FC is higher under UV irradiation as compared to ozonation. Therefore, almost complete hindering of pathogens could be achieved faster using UV irradiation. Table 3 shows a summary of the techno-economic aspects relevant to the three investigated methods for disinfection. The different processes of disinfection were investigated in terms of their capital as well as running costs. These costs were normalized to the volume of treated effluent that can be produced during 10 years of operation of the three processes (Leverenz et al. 2006).
The running cost for the chlorination system was evaluated based on the number of replaced chlorine drums (tanks) during the 10 years of operation. The total number of chlorine drums that have to be replaced depends mainly on the chlorine doses added to the treated effluent. The estimation of the total number of chlorine drums during the 10 years of operation is based on the average chlorine dose recommended in the current study (32 mg/L). The running cost in the ozonation process is essentially incurred for the replacement of the ozone cell. The cell requires replacement every 5 years on average basis. The running cost for the UV disinfection system is mainly for the replacement of the UV lamps. The average life span of the UV lamps in the market is about 9000 working hours.

In Figure 6, the costs, capital, running and total, are compared for the different disinfection processes under investigation. It is obvious from the figure that the total and capital costs for the disinfection of a cubic meter of the treated effluent follow the following order; Ozone > UV > Chlorine, where the values of the total cost per cubic meter are EGP 5.65, 1.78 and 0.96, respectively. In addition, the running cost for the disinfection of a cubic meter of the treated effluent follows the following order; UV > Ozone > Chlorine, with values of EGP per cubic meter of 0.44, 0.79 and 0.55, respectively.

Table 3: Comparison between the different investigated disinfection processes.

<table>
<thead>
<tr>
<th>Disinfectant</th>
<th>Optimum dose</th>
<th>Unit</th>
<th>Optimum contact time (min)</th>
<th>Capital cost EGP/m³</th>
<th>Running cost EGP/m³</th>
<th>Total cost EGP/m³</th>
<th>Environmental Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>32</td>
<td>mg/L</td>
<td>15</td>
<td>0.53</td>
<td>0.44</td>
<td>0.96</td>
<td>-</td>
</tr>
<tr>
<td>Ozone</td>
<td>15</td>
<td>mg/L</td>
<td>15</td>
<td>5.10</td>
<td>0.55</td>
<td>5.65</td>
<td>-</td>
</tr>
<tr>
<td>UV irradiation</td>
<td>164</td>
<td>mWs/cm²</td>
<td>15</td>
<td>0.99</td>
<td>0.79</td>
<td>1.78</td>
<td>-</td>
</tr>
</tbody>
</table>

Although chlorination proved to be the least expensive disinfection alternative with respect to the running and total costs, it still suffers from disadvantages that make it the least recommended process. These disadvantages may include:
1. Part of the chlorine added for disinfection remains in the wastewater as residual chlorine, which is toxic to aquatic life, even at low concentration, and may require dechlorination.
2. All forms of chlorine are highly corrosive and toxic. Thus, storage, shipping, and handling pose safety risks.

Fig. 6: Comparison of the costs (in Egyptian pounds) per cubic meter of treated effluent for the different disinfection processes.
3. The treated effluents of wastewater may contain concentrations of dissolved organic matter that may have not been removed in the course of treatment. The use of chlorine for disinfection of these effluents is likely to cause the formation of disinfection byproducts (DBPs). These can accumulate in the environment and are known to be toxic at certain concentration levels. Consequently, these materials or their precursors have to be removed from wastewater, which adds more costs to the treatment.

Conclusions:

The results obtained indicated that the three disinfectants under consideration namely; chlorine, UV irradiation and ozone were capable of producing a treated effluent free from pathogens. From the economic point of view, it was found that the total cost including capital and running costs follow an ascending order as follows: chlorination < UV irradiation < ozonation. However, the selection of an optimum disinfectant depends on various criteria including, but not limited to, cost, availability in the local market and environmental impact.

It is clear that chlorine is the least costly, but its residual value, even at low concentration is toxic to aquatic life and thus may require de-chlorination. Also, all forms of chlorine are highly corrosive and toxic thus storage, shipping and handling pose safety risks. UV irradiation, on the other hand, is clean and environmentally friendly. In addition, the use of ozone as a disinfectant has no harmful residuals that need to be removed after ozonation because ozone decomposes very rapidly. From the technical point of view, UV irradiation provides faster rates of inactivation for both total and fecal coliforms relative to ozonation.

In view of the technical, economic and environmental merits, UV irradiation is the most recommended among the three investigated disinfection options.

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