Meta-analysis of the reduction of antibiotic-sensitive and antibiotic-resistant *Escherichia coli* as a result of low- and medium-pressure UV lamps

Eithne O’Flaherty, Jeanne-Marie Membré and Enda Cummins

ABSTRACT

It is vital that harmful bacteria are removed from water and wastewater treatment plants to prevent human/environmental exposure. This paper examines the log reduction of antibiotic-sensitive (AS) and antibiotic-resistant (AR) *Escherichia coli* (*E. coli*) as a result of low-pressure (LP) and medium-pressure (MP) UV lamps. A meta-analysis was performed and a mixed-effect model was created in which 303 data points on the log reduction of *E. coli* from UV treatment were collected. The results show that in order to achieve a 6 log reduction using an MP lamp, on average a UV level of 7.3 mJ/cm² for AS *E. coli* and 7.5 mJ/cm² for AR *E. coli* were required. Using an LP lamp, a UV level of 8.1 mJ/cm² for AS *E. coli* and 8.4 mJ/cm² for AR *E. coli* were required. The results show there is no significant difference between the inactivation of AR and AS *E. coli* at different UV levels. The model predicts that AR or AS *E. coli* will be inactivated at UV levels lower than the recommended UV operation conditions (40 mJ/cm²), but it is important to use this UV level to inactivate other harmful microorganisms.

Key words | antibiotic resistance, *Escherichia coli*, meta-analysis, UV treatment

INTRODUCTION

In recent years UV systems have increased in popularity and are becoming more common in wastewater and water treatment facilities in Europe and North America (Guo et al. 2009). The main benefits of UV treatment systems are that they do not leave any chemical by-products behind, they are effective at eliminating harmful bacteria from water and they do not corrode the water treatment system (McKinney & Pruden 2012). When bacteria are exposed to UV the nucleotide base pairs in DNA molecules are damaged by the absorption of UV photons, which stops DNA replication and leads to the cell dying (Zimmer & Slawson 2002). There are different types of UV lamp: low-pressure (LP) UV lamps have a monochromatic emission at a wavelength of 254 nm, and medium-pressure (MP) UV lamps have polychromatic light at a broad range of wavelengths (between 200 and 600 nm) (Oguma et al. 2002). LP lamps are more commonly used in water and wastewater treatment facilities over MP lamps (Oguma et al. 2002). LP UV lamps are more frequently used due to the low cost of the product and its long lifespan, and they are more energy efficient than MP UV lamps (Ijpeelaar & Harmesen 2006). Regarding MP lamps, they are considered a better option for the prevention of bacteria recovering or reactivating after UV treatment (Oguma et al. 2002; Zimmer & Slawson 2002).

A large amount of research has been done to investigate the log reduction patterns of different bacteria and the different levels of UV required for inactivation (Hijnen et al. 2006; USEPA 2006; EPA 2011). However, antibiotic-resistant bacteria (ARB) are of growing concern to public health due to the difficulty of treating antibiotic-resistant (AR) diseases in patients, so it is important that harmful bacteria are inactivated or removed from water and wastewater treatment facilities. ARB and antibiotic-resistant genes (ARG) are making their way into the environment and their presence has been reported in the effluent water of drinking and wastewater plants (Armstrong et al. 1981; Xi et al. 2009; Galvin et al. 2010; Harris et al. 2012; Marti et al. 2013; Bai et al. 2015; El-Zanfaly 2015; O’Flaherty & Cummins 2017). It is therefore vital that continued research is carried out to ensure ARB are removed efficiently through water treatments in order to prevent environmental and human exposure to ARB. It is important to understand if ARB...
behave any differently to antibiotic-sensitive (AS) bacteria when exposed to UV treatment and to ensure that the appropriate UV level is used for the removal of ARB. Recommendations have been made by the EPA (2011) and the USEPA (2006) on the UV levels required for the log reduction of different AS bacteria.

Combining results from a range of scientific research could give a better overview of the UV level required for the log reduction of particular bacterial species. When combining previously published research studies, parameters such as the UV lamp type, whether the bacteria are resistant to antibiotics, different strains of bacteria and the UV level required for inactivation can be explored in more detail. A meta-analysis is a statistical method of combining data from individual comparable scientific research to create a strengthened study by giving a weighted average (Qian et al. 2004; Membré et al. 2013). A meta-analysis examining the effect of LP and MP UV lamps on AS and AR Escherichia coli using scientific literature has not been carried out, to our knowledge. The overall goal of this study was to gain a better understanding of the effect of UV treatment on AR E. coli, the effect of different UV lamp types on the log reduction of E. coli, the effect of UV on different E. coli strains and to give a weighted average UV level required for inactivation of E. coli. The dependent variable in the study was the reduction of E. coli expressed in log, the independent variable was the UV level expressed in mJ/cm² and the covariables were the study, strain, lamp type and whether the E. coli strains were resistant to antibiotics.

**MATERIALS AND METHODS**

**Data collection**

E. coli (AS and AR) was chosen for this study because it is frequently used as a biological indicator in determining the efficiency of water treatments, it is commonly used to study AR patterns (Ibekwe et al. 2011) and a large quantity of research has been carried out investigating the effect of UV on E. coli. An extensive literature search was carried out to find the log reduction values of AS and AR E. coli as a result of UV treatment. The data criteria required for a study to be included in the model were: a minimum of four E. coli log reduction values (i.e. to ensure precision, while values could range from 0 to 7 log reduction) as a result of UV treatment (UV values could range between 0.1 and 100 mJ/cm²), the strain type of E. coli, the type of UV lamp used (LP/MP lamp) and whether the E. coli bacteria were resistant or sensitive to antibiotics. A study was only included in the model if it fulfilled all of the data criteria requirements. The final data set used in the meta-analysis was a total of 303 E. coli log reduction values from 20 studies (259 AS E. coli data points and 44 AR E. coli data points; Supplementary Table, available with the online version of this paper).

Parameters considered but not included in this model were the possible reactivation/photoreactivation ability of E. coli after UV treatment and the experimental design of each study, in particular the aqueous solution the E. coli was suspended in during UV treatment. Only a small number of studies reported on the possibility of E. coli photo-reactivating, which is why this parameter was not included in the model. The aqueous solution the E. coli was suspended in for the UV treatment experiments varied from study to study (approximately 55% used phosphate buffer saline, 25% used 0.9% sterilized saline solution and the remaining studies used either wastewater, surface water or peptone water). There was insufficient data on each solution type, hence this parameter was not included in the model. According to research there is no inactivation difference between E. coli bacteria suspended in phosphate-buffered saline, surface water (from a reservoir), water from a drinking water treatment plant (after sand filtration) and filtered wastewater effluent (Hu et al. 2012; McKinney & Pruden 2012).

**Mixed-effect meta-analysis model**

The log reduction of E. coli as a result of UV treatment was analysed in a mixed-effect model where both fixed and random factors were included. The fixed factors in the model were the UV lamp type and whether the bacteria were resistant to antibiotics. The random factors were the study and E. coli strain type. A mixed-effect model allows for uncertainty to be accounted for when using data from different sources (Qian et al. 2004; Gelman & Hill 2007; Gronewold et al. 2009). The meta-analysis model was created by combining three linear models to create one nonlinear model (Equation (1)). Although the model structure was simple, it enabled testing on whether there is any UV threshold before any log reduction.

\[
\log R = \begin{cases} 
0 & \text{if } UV < UV_{\text{min}} \\
\text{Slope}_{\text{adj}} \times (UV - UV_{\text{min}}) + \epsilon & \text{Plateau when } UV \rightarrow \text{max } UV 
\end{cases}
\]

Log R is the log reduction of E. coli as a result of UV treatment. UV is the UV level (mJ/cm²). UV_{min} is the
minimum UV level before the bacteria start to log reduce as a result of UV and an effect of the study (i is the study number, from 1 to 20). \( \text{Slope}_{ijkl} \) is the slope of the log reduction of the bacteria as an effect of the study, strain (j is the strain number, from 1 to 27), lamp type (k is the lamp type: 1 = LP lamp, 2 = MP lamp) and resistance to antibiotics (l is bacteria resistant to antibiotics: 1 = sensitive to antibiotics, 2 = resistant to antibiotics). Plateau is the maximum log reduction of bacteria when UV tends to infinity (i.e. maximum UV). Plateau is defined as a fixed value, \( 7 \log \) for the maximum log reduction. \( \epsilon \) is the error, \( \epsilon \sim \text{normal}(0, \sigma_{\log R}^2) \). \( \text{UV}_{\text{ave}} \) (Equation (2)) is described as follows:

\[
\text{UV}_{\text{min}} = \text{UV}_{\text{ave}} + \theta_i \tag{2}
\]

\( \text{UV}_{\text{min}} \) is the minimum UV level before the bacteria start to reduce. \( \text{UV}_{\text{ave}} \) is the average minimum UV. \( \theta \) is the random effect of the study, \( \theta_i \sim N(0, \sigma_{\text{study lag}}^2) \), parameterized so that the sum of the study effect was null: \( \sum \theta_i = 0. \) The slope (Equation (3)) is described as follows:

\[
\text{Slope}_{ijkl} = \text{Slope}_{\text{ave}} + \alpha_i + \beta_{ij} + \beta_{jk} + \sigma_{\text{str}} + \gamma_l \tag{3}
\]

\( \text{Slope}_{ijkl} \) is the slope. \( \text{Slope}_{\text{ave}} \) is the average slope. \( \alpha_i \) is the random effect of the study, \( \alpha_i \sim N(0, \sigma_{\text{study slope}}^2) \), parameterized so that the sum of the study effect was null: \( \sum \alpha_i = 0. \) \( \beta_{ij} \) and \( \beta_{jk} \) are the random effect of the strain, AS and AR respectively. \( \beta_{ij} \sim N(0, \sigma_{\text{strain slope}}^2) \) and \( \beta_{jk} \sim N(0, \sigma_{\text{strain slope}}^2) \), parameterised so that the sum of the AS strain effect was null: \( \sum \beta_{ij} = 0 \) and the AR strain effect was null: \( \sum \beta_{jk} = 0. \) \( \delta \) is a fixed effect of the lamp type (\( \delta_2 = -\delta_1 \)). \( \gamma \) is a fixed effect of AS/AR bacteria (\( Y_2 = -Y_1 \)).

### Statistical software and Bayesian inference

The statistical software used to create the meta-analysis model was the WinBUGS software (version 1.4.3). Bayesian statistical inference was used and prior probability distributions were defined for the model (Table 1). The type of distributions used to represent each prior were chosen based on parameter definition and statistical constraint. Monte Carlo simulations were run to estimate the probability distributions for the model parameters. The model was run for 50,000 iterations and the first 20,000 iterations (burn-in period) were removed.

### Table 1 | Bayesian inference prior probability distributions defined for the model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Distributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{UV}_{\text{ave}} )</td>
<td>~ normal(0, 0.001)</td>
</tr>
<tr>
<td>( \text{Slope}_{\text{ave}} )</td>
<td>~ normal(0, 0.001)</td>
</tr>
<tr>
<td>Plateau</td>
<td>~ normal(6, 0.1)</td>
</tr>
<tr>
<td>( \sigma_{\log R} )</td>
<td>~ uniform(0, 5)</td>
</tr>
<tr>
<td>( \sigma_{\text{study lag}} )</td>
<td>~ uniform(0, 10)</td>
</tr>
<tr>
<td>( \sigma_{\text{study slope}} )</td>
<td>~ uniform(0, 10)</td>
</tr>
<tr>
<td>( \sigma_{\text{strain slope}} )</td>
<td>~ uniform(0, 10)</td>
</tr>
<tr>
<td>( \delta_k )</td>
<td>( k_1 \sim \text{normal}(0, 0.001); k_2 = -k_1 )</td>
</tr>
<tr>
<td>( \gamma_l )</td>
<td>( l_1 \sim \text{normal}(0, 0.001); l_2 = -l_1 )</td>
</tr>
</tbody>
</table>

### Model cross validation

The leave-one-out cross-validation method was used to validate the model. One data point at a time was removed (randomly) and the model was run without that data point; this was done 50 times (10% of the data set). The bias factor (Equation (4)) and accuracy factor (Equation (5)) were calculated with the 50 data validation points using the method described by Ross (1996).

\[
\text{Bias factor} = 10^{(\log(\text{Pred}/\text{Obs})/n)} \tag{4}
\]

\( \sum \log \) is the sum of the log values, \( \text{Pred} \) is the values predicted by the model and the \( \text{Obs} \) are the values that were observed in the scientific literature, \( n \) is the number of data points used in the leave-one-out cross-validation method (\( n = 30 \)).

\[
\text{Accuracy factor} = 10^\left(\sum \log(\text{Pred}/\text{Obs})/n\right) \tag{5}
\]

The difference between the bias and accuracy factor equations is that the absolute values are used in the accuracy factor equation.

### RESULTS

### Meta-analysis and model validation results

The predicted log reduction values from the meta-analysis model versus the observed log reduction values from the scientific research papers are plotted in Figure 1; this includes all the data points (303). The model gives satisfactory results with a residual standard deviation of 0.66,
which is close to the commonly accepted microbiological error of 0.5 (Pujol et al. 2012; Ben-David & Davidson 2014) and meaningful confidence intervals (Table 2). However, due to the parameterization with the plateau set to a maximum of 7 log reduction (the maximum log reduction value found in the observed data), this model predicts the UV level required for the bacteria to start to log reduce up to 7 log reduction (Figure 1). It does not show the UV level required for a log reduction above 7; it is important to keep in mind that 10 mJ/cm² is above the average UV level required for 7 log reduction (Figure 3).

The results from the cross validation show good correlation (Figure 2). The results from the 30 validation points show a bias factor result of 1.1, showing the predicted results were greater than the observed values by 10%. The accuracy factor result was 1.2, showing on average there is a 20% difference (smaller or larger) between the predicted and observed values. Statistically the model created here gives satisfactory results and provides useful information. However, it could be strengthened with more detailed data from scientific research. In particular, more data on the effect of UV on AR E. coli and on different strains of E. coli could help improve this model further.

Table 2 | Parameter estimates from the mixed-effect model: mean, standard deviation (SD), 2.5% credibility interval, median and 97.5% credibility interval

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>SD</th>
<th>2.5%</th>
<th>Median</th>
<th>97.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVAve</td>
<td>0.94</td>
<td>0.25</td>
<td>0.49</td>
<td>0.94</td>
<td>1.40</td>
</tr>
<tr>
<td>SlopeAve</td>
<td>0.88</td>
<td>0.07</td>
<td>0.76</td>
<td>0.87</td>
<td>1.01</td>
</tr>
<tr>
<td>σlogR</td>
<td>0.66</td>
<td>0.03</td>
<td>0.60</td>
<td>0.66</td>
<td>0.72</td>
</tr>
<tr>
<td>σstudy log</td>
<td>1.31</td>
<td>0.37</td>
<td>0.69</td>
<td>1.27</td>
<td>2.16</td>
</tr>
<tr>
<td>σstudy slope</td>
<td>0.23</td>
<td>0.07</td>
<td>0.13</td>
<td>0.22</td>
<td>0.38</td>
</tr>
<tr>
<td>σstrain slope</td>
<td>0.58</td>
<td>0.14</td>
<td>0.36</td>
<td>0.56</td>
<td>0.89</td>
</tr>
<tr>
<td>δ1 (δ2 = −δ1)</td>
<td>−0.06</td>
<td>0.01</td>
<td>−0.08</td>
<td>−0.06</td>
<td>−0.03</td>
</tr>
<tr>
<td>γ (Y2 = −Y1)</td>
<td>0.02</td>
<td>0.07</td>
<td>−0.12</td>
<td>0.03</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Average predicted log reduction

Figure 3 shows the average predicted log reduction for AS and AR E. coli as a result of LP and MP UV lamps. Results show that there is not a significant effect of AR on the log reduction of E. coli (γ is 0.02 log, Table 2). This demonstrates that on average the UV treatment of AS and AR E. coli have similar log reduction patterns and require similar UV levels for a 6 log reduction. The lamp type has a small but a significant effect on the log reduction of the bacteria (δ is 0.06 log, Table 2). The results indicate that in order to achieve a 6 log reduction with an MP lamp, a level of 7.5 mJ/cm² UV is required for AS E. coli and 7.5 mJ/cm² UV for AR E. coli (Figure 3). To achieve the same log reduction using an LP lamp, 8.1 mJ/cm² UV is required for AS and 8.4 mJ/cm² UV for AR E. coli (Figure 3). The average predicted results also show that the effect of the lamp becomes more important at higher reduction levels: there is divergence between the two lamps the greater the log reduction and UV level (Figure 3).
Effect of the study on log reduction

The results show an effect of the study on the UV min ($\sigma_{\text{study lag}}$ is 1.3 SD, Table 2). This indicates variability between the studies on the level of UV required for the bacteria to start to reduce. For example, in studies 2 and 4, the bacteria start to reduce at a higher UV level compared to the other studies (Figure 4). In contrast studies 3 and 13 start to reduce at a lower UV level compared to the other studies (Figure 4). There is also an effect of the study on the slope ($\sigma_{\text{study slope}}$ is 0.23 SD, Table 2), showing some variability of the log reduction slopes as an effect of the different studies (Figure 5).

Effect of strain on log reduction

The results show there is an effect of the strain on the slope ($\sigma_{\text{strain slope}}$ is 0.58 SD, Table 2). This shows that different strains of E. coli have different log reduction patterns. Strain 5 (O157:H7 CCUG 29199) has a steep log reduction slope caused by a low UV level compared to the other strains, this particular strain being very sensitive to the UV treatment (Figure 6). In contrast, strain 25 (ampicillin-resistant CGMCC 1.1595) has a gradual log reduction slope and requires a high UV level, showing this particular strain is more resistant to UV (Figure 6). To demonstrate the strain effect clearly, Figure 7 shows the different log reduction patterns of strains 17, 18, 19 and 21 from the same study (Quek & Hu 2008).

DISCUSSION

The Austrian standards for UV treatment state that 40 mJ/cm² UV level is required to ensure a 6 log reduction of bacteria in drinking water (Austrian Standards Institute 2001). According to the USEPA (2006) a typical E. coli UV dose response curve using an LP UV lamp required approximately 11 mJ/cm² for a 6 log reduction of the bacteria. The results from this model showed an average predicted UV level of 8.1 mJ/cm² was required for a 6 log reduction of AS E. coli. The average predicted results also show...
that using an LP or MP UV lamp required similar UV levels to achieve a 6 log inactivation, with MP lamps requiring a lower level of UV to achieve the log reduction (Figure 3). However, it is important to consider both economic requirements and the infrastructure of a treatment plant when deciding on a lamp type, so decisions should be made on a case-by-case basis. Even though LP UV lamps are more energy efficient, less costly and have a longer lifespan, it is difficult to conclude that they are more suitable for UV disinfection of E. coli bacteria (Ijpeelaar & Harmsen 2006). It is also important to consider the possibility of dark repair and photoreactivation of bacteria after UV treatment and to use a suitable lamp that does not allow the bacteria to recover (Guo et al. 2009).

Dark repair requires several proteins that work together to remove DNA damage within the cell after UV treatment, and the recovery process can occur in dark conditions after UV exposure (Friedberg et al. 1995). This type of recovery process was first examined by Harm (1968) in E. coli. However, several authors in recent times examined dark repair in E. coli and found little or no recovery through dark repair but did find the bacteria could recover through photoreactivation (Sommer et al. 2000; Zimmer & Slawson 2002; Guo et al. 2002). Photoreactivation is the process whereby bacteria repair the damage caused by UV treatment within a few hours of being exposed to visible light or near UV; this can be a considerable disadvantage of UV treatment (Oguma et al. 2002; Guo et al. 2012). According to Oguma et al. (2002) the majority of E. coli strains have the capability to photoreactivate after UV treatment. Research suggests that MP lamps may have an advantage over LP lamps with regards to photoreactivation. MP lamps have a broad range of wavelengths (UV-A 320–400 nm; UV-B 290–320 nm; UV-C 190–290 nm) and have been shown to be more successful at preventing photoreactivation of bacteria after UV treatment (Oguma et al. 2002; Zimmer & Slawson 2002). Research also suggests that a higher level of UV is required to ensure bacteria do not recover after UV treatment. Hoyer (1998) found that in order to get a 4 log reduction of E. coli (strain ATCC 1.1229) a UV level of 10 mJ/cm² was required but when considering photoreactivation for 2 hours after UV treatment, a UV level of 30 mJ/cm² was required. Sommer et al. (2000) found that a very low UV level of 1.2 mJ/cm² was required for a 6 log reduction E. coli (strain O157:H7 CCUG 29199) but when photoreactivation was examined a UV dose of 30 mJ/cm² was required. To ensure full disinfection of bacteria and any recovery potential, it is necessary to use a high UV level, as recommended by the Austrian standards. It is important to consider the photoreactivation capabilities of bacteria when considering lamp type and UV level, especially if the bacteria are going to be exposed to visible light after UV treatment.

The model showed an effect of the strain: different E. coli strains had different log reduction patterns as a result of UV treatment (Figures 6 and 7). O157:H7 CCUG 29199 (strain 5) showed a high log reduction at a low UV level, which is positive as the O157 strains can be a serious risk to human health (Sommer et al. 2000). The level of UV required to start log reduction (effect of study on UVmin) varied between the studies, with the studies requiring varying UV levels for the bacteria to start to reduce (Figure 4). A possible reason for the varying log reduction patterns between the E. coli strains and the UV level required for the bacteria to start to log reduce may be to do with the growth phase of the bacteria. Mofidi et al. (2002) examined five strains of E. coli that had similar growth phases with regards to the lag, exponential, stationary and death phases. Then Mofidi et al. (2002) examined the effect of a 3 mJ/cm² UV level on the E. coli when it was 3 hours (mid-exponential) and between 14 and 18 hours (late stationary) into the growth phase. The results showed a log reduction of 5.5 and 1.5 with the same UV level, respectively (Mofidi et al. 2002). This shows a possible difficulty when treating bacteria with UV: the bacteria may not be stressed by the surrounding environment and therefore in a dormant state, which can make the bacteria more resistant to UV treatment (Mofidi et al. 2002).

The average log reduction results show AS and AR E. coli had similar log reduction patterns, which is in agreement with several scientific research papers (Figure 3). According to Guo et al. (2012) E. coli with the ampicillin-resistant plasmid had a log reduction similar to other AS strains of E. coli. Templeton et al. (2009) found that the log reduction of ampicillin- and trimethoprim-resistant E. coli were similar to AS E. coli. Huang et al. (2013) also had similar log reduction patterns for both AS and E. coli resistant to tetracycline. However, it has been suggested by Meckes (1982) that tetracycline-resistant E. coli has tet proteins that may protect the bacteria from UV treatment, making it more difficult to eliminate with UV treatment. It has also been implied that the presence of certain plasmids such as the N group R46 plasmid (confers sulfonamide, ampicillin, tetracycline and streptomycin resistance) can make bacteria more difficult to treat with UV (Drabblewe & Stockerb 1968; Tribe & Pinney 1977). Pang et al. (2016) found that E. coli resistant to ampicillin was more resistant at lower UV doses (5 and 20 mJ/cm²),
but when a dose of 40 mJ/cm² was used it resulted in a 5.5 log reduction. With the variability reported in the research and as a precaution, the recommended level of 40 mJ/cm² should be used to ensure inactivation of AR \textit{E. coli}, to prevent photoreactivation, while also inactivating other potential harmful microorganisms that may be more resistant to UV (e.g. \textit{Cryptosporidium} or Poliovirus). Further investigation into treating AR \textit{E. coli} with UV could strengthen this model, but this model still provides important information on the behaviour of AR and AS \textit{E. coli} when treated with UV. The results generated by this paper could be used to improve risk assessment models examining the effect of UV treatment on AR or AS \textit{E. coli}. Risk assessment models examining the human exposure to AR \textit{E. coli} through drinking water or examining the impact of a wastewater treatment plant located near a recreational site could use this data to predict AR or AS \textit{E. coli} concentrations after UV treatment (O’Flaherty et al. 2018). There is an urgent need for environmental risk assessments investigating ARB (Manaia 2017) and this study is a contribution to the research gap in this area.

\section*{CONCLUSION}

A meta-analysis model was created to provide a clearer insight into the effect of UV on \textit{E. coli} by investigating different parameters (UV lamp type, different \textit{E. coli} strains and AR). This study gives a weighted average of the log reduction pattern of AR and AS \textit{E. coli} as a result of UV treatment with LP and MP UV lamps. The results show MP lamps required a lower level of UV in comparison to LP UV lamps to achieve a 6 log reduction of \textit{E. coli}. LP lamps are more economical but MP UV lamps are considered better at preventing photoreactivation if treated water is exposed to day-light. Therefore, when deciding on a lamp type for a water treatment system, both the economic requirement and the infrastructure of the water treatment plant should be considered. An MP lamp could be more suitable for treatment plants where the treated water is exposed to daylight; but if the treated water is not exposed to daylight, LP lamps could be more suitable due to the economic benefit. The model also showed that \textit{E. coli} AS or AR have similar log reduction patterns in agreement with reported work. This type of information is valuable in creating more accurate risk assessment models investigating the effect of UV on AR and AS \textit{E. coli}.

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