Tailing propensity in the ultraviolet disinfection of trickling filter and activated sludge wastewater treatment processes

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ABSTRACT

In this paper, the effect of suspended flocs on the tailing of ultraviolet (UV) disinfection kinetics of secondary effluents was examined. To achieve this goal, final effluents produced in two processes for treating wastewater; namely, a trickling filter system and an activated sludge system, were collected and their UV disinfection were compared. Tailing of the UV dose response curve was controlled by the fraction of flocs that are both culturable and UV-resistant, referred to as the ‘tailing propensity’. Using this parameter, the contribution of various floc size fractions in reducing the UV disinfection efficiency of wastewater samples was quantified. Activated sludge flocs larger than 125 μm exhibited as much as 35 times greater tailing propensity than smaller flocs in the range of 20–25 μm. Within a fixed size range, the tailing propensity of flocs generated in the trickling filter system was 3 to 8 times higher than that of activated sludge flocs, and this difference increased with the floc size. A mathematical model was developed to predict the UV disinfection of secondary effluents from suspended particle size distribution data. The model showed good agreement with experimental results.

Key words | floc, modeling, secondary effluent, tailing, ultraviolet disinfection

INTRODUCTION

Ultraviolet (UV) irradiation is an effective method of wastewater disinfection as it is comparatively a much cleaner technology without any quantifiable adverse toxicological effects (Blatchley et al. 1991; Matasci et al. 1999). It works by causing damage to cellular DNA, thereby inactivating the reproduction of microorganisms (Pfeifer et al. 2005; Piluso & Moffatt-Smith 2006). In UV disinfection, the rate of microbial inactivation typically follows a first-order kinetic at low UV doses. At higher doses, i.e. approximately 30 mJ/cm² and above (Qualls et al. 1985), the disinfection rate often decreases drastically, resulting in a near plateau region termed as the tailing region. One of the key factors influencing the level of tailing is presence of particle-associated bacteria, which are embedded in and protected by the wastewater flocs (Darby et al. 1993; Emerick et al. 2000; Farnood 2004; Mamane 2008). Other factors that affect the tailing of UV disinfection are strain resistance, dormancy,
cell growth status, and strain variability (Mofidi et al. 2002). Several studies have demonstrated that effluents containing larger flocs show a greater tailing tendency when disinfecting with UV light (Yong et al. 2008; Azimi et al. 2014a). Larger flocs provide more coliform protection in the form of shielding effects such as absorption, scattering, and blocking (Cairns et al. 1993; Farnood 2004; Madge & Jensen 2006; Azimi et al. 2012; Kollu & Örmeçi 2012). Azimi et al. (2012, 2014a) showed that in addition to size, UV disinfection kinetics was affected by flocc compactness, which are influenced by operational parameters such as temperature and influent phosphorus levels. In addition, it has been reported that the chemical composition of flocs, such as the presence of naturally occurring polyphosphates as occurs in the biological phosphorus removal processes, could significantly affect the UV disinfection rate (Azimi et al. 2013, 2014b). Therefore, changes in the wastewater treatment process that potentially affect flocs physicochemical characteristics could change the response of the system to UV irradiation.

The above studies were mainly focused on suspended growth wastewater treatment systems. Trickling filters, on the other hand, are attached-growth biological beds with filter media supporting microbial growth on their surface. Beside simplicity, this process has advantages such as supporting the growth of a wider range of microorganisms (slow growing microbes such as nitrifiers), and allowing the degradation of a wider range of organic substrates and ammonia (Bishop 1997; Berdanier et al. 2010). The main source of flocs in trickling filter effluents is the detachment from biofilms as a result of external forces overcoming the internal strength of the matrix that bind the biofilm together (Hon et al. 2003). Biofilms are known to be typically heterogeneous structures (Zhang & Bishop 2001; Sharma et al. 2009; Viana et al. 2012) with spatial, physical and chemical variations. When biofilms grow and thicken, zones with limited substrate and oxygen could develop. Detachment of biofilm could also take place as a result of the endogenous decay of microorganisms within these zones. Zhang & Bishop (2001) investigated the dissolved oxygen profile of biofilms and found that well-defined aerobic and anoxic layers existed within the biofilm, even when the biofilm developed under aerobic conditions. Furthermore, extracellular polymeric substance content was reported to decrease with biofilm depth (Zhang & Bishop 2001; La Motta et al. 2003) while the biofilm density increased with depth by as much as ten times (Masuda et al. 1991; Laspidou & Rittmann 2004).

The distinct structure of biofilms is expected to affect the structure of suspended flocs and hence their UV disinfection kinetics. In fact, trickling filter effluents are known to be more resistant to UV disinfection. Sakamoto et al. (2001) concluded that final effluents from fixed film processes generally required a higher UV dose compared to suspended growth systems to achieve the same level of disinfection performance. In their study, however, variations in effluent quality such as UV transmittance (UVT) and effluent total suspended solids (TSS) was not taken into account when comparing the UV dose demand of difference processes. Emerick et al. (1999) similarly reported that the average number of coliform bacteria surviving UV doses higher than 100 mJ/cm² in the trickling filter effluent was approximately double of that in the conventional activated sludge process. However, in that study, the TSS of the trickling filter effluent was more than three times that of the activated sludge effluent. Loge et al. (1999) suggested that the lower disinfectability of the trickling filter effluents could be attributed to their poor effluent quality in terms of the level of suspended solids – a problem often associated with the trickling filter process. However, it is not clear whether the trickling filter flocs have a higher resistance to UV disinfection, or simply the higher effluent TSS causes the lower disinfection levels compared to suspended growth systems.

In this paper, the effect of suspended flocs on the tailing of UV disinfection kinetics of secondary effluents is examined. The objective is to develop a better understanding of floc characteristics that affect the tailing of UV dose response curve (DRC) of secondary effluents. Earlier field studies suggest that fixed film secondary treated effluents resulted in a higher tailing of UV DRC than suspended growth processes (Sakamoto et al. 2001). Therefore, trickling filter and activated sludge effluents were chosen as examples of processes that generate flocs with different characteristics. Culturability and UV resistance of these floc samples were determined as a function of their size based on standard plate count technique using fecal coliform as indicator organism. It should be pointed out that systematic comparison of these two treatment processes requires side-by-side evaluation of these systems under comparable operating conditions that was outside the scope of this work. A mathematical model is developed to estimate the effect of suspended particles on the kinetics of UV disinfection based on particle size distribution (PSD) data. The results of this study may be employed to devise real-time control schemes or to optimize the implementation of filtration or other upstream processes for improving the design and operation of UV disinfection systems.
Tailing propensity

It has been shown that the double-exponential model may be used to describe the UV inactivation kinetics of wastewater flocs (Azimi et al. 2012):

\[ N = (1 - \beta) N_0 e^{-k_1 D} + \beta N_0 e^{-k_2 D} \]  \hspace{1cm} (1)

where \( N \) is the residual number of culturable flocs per unit volume after UV irradiation in colony forming unit (CFU)/100 mL, \( N_0 \) is the initial number of culturable flocs in unit volume in CFU/100 mL, and \( D \) is the delivered UV dose in mJ/cm². The parameter \( \beta \) represents the fraction of UV-resistant flocs and, finally, \( k_1 \) and \( k_2 \) are the first-order inactivation rate constants for the UV-susceptible and UV-resistant fractions, respectively.

In assessing UV disinfection efficiency, the number of particle-associated coliform bacteria plays a critical role (Emerick et al. 1999; Loge et al. 2001). Hence, it is important to quantify the percentage of culturable flocs, \( P \), which refers to the flocs containing at least one culturable coliform bacterium. In this study, it is assumed that the likelihood that a given suspended particle is cultivable (based on standard plate count technique using fecal coliform as the indicator organism) is given by parameter \( P \), hence:

\[
\text{[Concentration of culturable flocs]} = \frac{\text{[Total floc concentration]}}{\text{[Probability that a floc is culturable]}}
\]

Therefore, \( P \) can be determined experimentally by dividing the concentration of culturable flocs, \( N_0 \), by the total floc concentration, \( N_p \), in a sample:

\[ P = \frac{N_0}{N_p} \]  \hspace{1cm} (2)

Based on Equation (2), changes in the total floc count directly affect the initial number of CFUs (\( N_0 \)). Naturally, everything else being the same, an increase in \( N_p \) will directly increase \( N \) at a given delivered UV dose. Accordingly, Equation (1) can be written in terms of the total floc concentration as:

\[ N = (1 - \beta) P N_p e^{-k_1 D} + \beta P N_p e^{-k_2 D} \]  \hspace{1cm} (3)

At high UV doses where the contribution of UV-susceptible fraction becomes insignificant, Equation (1) can be simplified to:

\[ N = \beta N_p e^{-k_2 D} \]  \hspace{1cm} (4)

Equation (4) closely approximates the tailing region of UV DRC at high doses. This equation shows that the UV inactivation in the tailing region of UV DRC is controlled by two parameters: (1) the inactivation rate constant of UV-resistant flocs or \( k_2 \), and (2) the tailing level (\( \beta N_0 \)). Earlier studies have shown that the rate of inactivation (i.e. slope) of the tailing region, \( k_2 \), is independent of floc size, however, \( \beta \) and hence the tailing level increases with the floc size (Azimi et al. 2012). By using Equation (2), the above equation can be converted to:

\[ N = \beta P N_p e^{-k_2 D} \]  \hspace{1cm} (5)

Equations (3) and (5) relate the surviving CFUs (\( N \)) to the total floc count (\( N_p \)) that in turn is related to the TSS. Based on the latter equation, the number of surviving CFUs, \( N \), in the tailing region is directly proportional to \( P \times \beta \) that is denoted by TP and is referred to as the tailing propensity. TP represents the fraction of total flocs that are both culturable (as determined by standard plate count method using indicator organisms) and UV resistant. This parameter quantifies the portion of suspended particles that contribute to the tailing level of UV DRC. Therefore, at the same concentration of suspended particles, \( N_p \), effluents with a larger fraction of viable particles, \( P \), and/or more UV-resistant particles, \( \beta \), will have a higher TP and will exhibit a higher tailing level. Hence, a small TP value shows that most of the wastewater flocs are either not culturable or not UV-resistant. On the other hand, assuming TP to be a constant, a higher total floc concentration, \( N_p \), will result in a larger surviving CFU, \( N \), simply because a higher \( N_p \) means a larger initial concentration of culturable flocs, i.e. \( N_0 \), see Equation (2). It should be noted that higher \( N_0 \) is known to intensify the absorption and scattering of UV light and reduce the UV disinfection rate; however, such effects are taken into account through the commonly used correction factors for calculating the delivered UV dose (Bolton & Linden 2003).

The above discussion is not limited to floc suspensions. The double exponential model and hence Equations (3) and (4) are also applicable to the UV DRC of whole effluent (Yong et al. 2009). In the latter case, \( N_p \) represents the total suspended particle concentration that is related to the effluent suspended solids. In this case, the number of
surviving CFUs can be estimated by adding the coliform survival rate for individual size fractions:

\[ N = \sum_{i} P_i N_{pi} \left[ (1 - \beta_i) e^{-k_i D} + \beta_i e^{-k_2 D} \right] \quad (6) \]

where subscript ‘i’ refers to the i-th particle size fraction.

The above approach offers the opportunity not only to investigate effect of suspended flocs on the UV disinfectability of effluents but also to estimate the UV DRC based on the particle count data.

**MATERIALS AND METHODS**

**Sample collection**

Suspended growth activated sludge mixed liquor and final effluent samples were collected from Ashbridges’ Bay municipal wastewater treatment facility, located at the eastern end of the city of Toronto. The plant has a capacity of 818,000 cubic meters per day and utilizes an activated sludge biological system for secondary treatment along with primary and secondary sedimentation. Trickling filter samples were collected from Harmony Creek Water Pollution Control Plant, located in the Durham Region, 65 km east of the city of Toronto. The plant has a capacity of 68,200 m^3 per day and half of the secondary treatment processes comprise of trickling filtration facilities. Both plants received municipal wastewater influents, and samples were collected from the two treatment plants within 1–2 days (to reduce seasonal/precipitation variabilities). Samples were collected on the day of the experiment from both of the local municipal wastewater treatment plants.

**Sample filtration and sieving**

To separate flocs from wastewater samples, two sieve trays (U.S.A. Standard Testing Sieve) were stacked with the tray having a larger opening on top. Mixed liquor was then poured through and floc sample was collected from the bottom sieve. This was then gently washed under MilliQ water for 15 min to remove any smaller flocs still trapped within the sample. The sample was then back-washed from the sieve tray and collected in a container. Finally, the fractionated samples were diluted with MilliQ water to the appropriate particle concentration and analyzed for their PSD and concentration.

Filtered samples were prepared by slowly pouring the final effluent (collected after the secondary clarifier) onto the desirable sieve and gentle washing using MilliQ water. The filtrate was then collected for additional testing. Similarly, to prepare samples containing free floating fecal coliforms, activated sludge effluent was filtered using an 8 µm Whatman filter paper and the filtrate was collected for analysis.

**Particle size distribution**

PSD analysis was carried out using a Multisizer 3.0 particle analyzer (Beckman Coulter Canada, Mississauga, Ontario, Canada). Fractionated samples were diluted with a 10.7 g/L solution of NaCl to the appropriate concentration and analyzed to obtain the size distribution and the number concentration (N_p) of flocs. It should be noted that since Multisizer operates based on Coulter principle, it underestimates the actual size of porous particles such as those found in wastewater (Kachel 1986; Yuan et al. 2009). Therefore, to convert the measured particle size to the corresponding sieve size the following correction was used (Yuan et al. 2009):

\[ D_{\text{sieve size}} = 2.14 \times D_{\text{Coulter}} \quad (7) \]

The above equation was employed to divided the PSD of effluent into particle size ranges corresponding to the sieve size fractions used in this study.

**UV bioassay**

A collimated beam apparatus equipped with a low pressure mercury UV lamp was used to irradiate the samples (Trojan Technologies, London, Ontario, Canada). Twenty milliliters of sample was placed in a Petri dish, 4.8 cm in diameter, and stirred with a magnetic stirrer throughout the irradiation. The UV doses that the samples received ranged from 10 to 70 mJ/cm^2. The UV light intensity was measured using an IL1700 radiometer equipped with a SED240 sensor and NS 254 filter (International Light, Newburyport, MA, USA). Lambda 35 UV/Vis Spectrometer (Perkin Elmer) equipped with an Integrating Sphere device (Labsphere RSA-PE-20) was used to measure the UVT at 254 nm. The exposure time for each dose was calculated based on the measured intensity and UVT following the procedure described by Bolton & Linden (2003).

The irradiated samples were then cultured using the membrane filtration method following Standard Methods.
for the Examination of Water and Wastewater (# 9222 A, APHA 2001). m-FC Agar (VWR, Mississauga, Ontario) was used as the culturing media and the buffer solution used for rinsing was 13.6 g/L KH2PO4 at pH 7.2. Samples were incubated at a temperature of 45 °C for 24 ± 3 hours, and the number of CFUs were enumerated. It should be noted that this method is based on detecting fecal coliform (as indicator organism) and does not enumerate all the microorganisms present in the sample. The method used in this work is commonly applied as the standard method in the water and wastewater quality monitoring.

Plots of CFU/100 mL versus the UV dose, known as UV DRC, were used to estimate the values of k1, k2, and β based on non-linear regression using Mathematica™ v.5.2 software (Wolfram Research, Champaign, IL, USA).

The percentage of culturable flocs, P, was determined by dividing the concentration of culturable flocs (determined from culturing floc samples prior to UV irradiation) by the number concentration of flocs (determined from particle size analysis) as per Equation (2).

**Statistical analysis**

The statistical significance of the results was tested by performing student t-test. All UV DRC data were collected in triplicates (or more). The student t-test was performed in pairs for β, P, k1, and k2 using α = 0.05. Therefore, if the calculated p-value was smaller than 0.05, the difference between the two samples was deemed to be statistically significant.

**RESULTS AND DISCUSSION**

**Significance of large flocs in UV disinfection tailing**

Figure 1 shows the UV DRC of filtered and unfiltered activated sludge effluent. The results show that by removing large flocs via filtration, the tailing level was lowered significantly. At the UV dose of 60 mJ/cm², the concentrations of surviving CFU for the 75 μm and 32 μm filtered samples were 0.5 log and 1 log lower than that of unfiltered effluent, respectively. Furthermore, it can be seen that the effluent initial fecal coliform count (N0) did not significantly vary (p-value = 0.25) by removing particles larger than 32 or 75 μm.

Comparison of the PSD of filtered and unfiltered effluent samples (Figure 2) suggests that the tailing level of UV DRC is mainly controlled by the presence of larger flocs. In both filtered samples, only small amounts of the flocs in the size range of 10–45 μm were removed by sieving; namely 15% for the 32 μm filtered sample and <1% in the case of 75 μm filtered sample. Yet more than 80% reduction in the tailing level of UV DRC was achieved in both scenarios. In contrast, the removal rate of large flocs in the size range of 45–53 μm were 70% and 50% for the 32 μm and 75 μm filtered samples, respectively.

Using the UV DRCs of various effluent fractions presented in Figure 1, the relative contribution of different floc size fractions to the number of surviving CFUs could be estimated. Figure 5 demonstrates the percent contribution of each size fraction to the surviving CFUs at different UV doses. The % contribution of filtered effluents (<32 μm and <75 μm) to UV DRC were estimated by dividing the number of CFU/100 mL in the filtered samples by the corresponding values in the unfiltered sample at each dose. Accordingly, the contributions of >32 μm and >75 μm fractions and hence that of 32–75 μm can be determined. The results show that at low UV doses (<10 mJ/cm²) the concentration of CFUs was dominated by the small size flocs (<32 μm). However, these small flocs were rapidly disinfected and their contribution vanished.
beyond the dose of 20 mJ/cm². At the onset of the tailing region (UV dose of about 30 mJ/cm²), the 32–75 μm fraction was the main contributor to the number of CFUs, while it was the large (i.e. >75 μm) flocs that controlled the tailing level of UV DRC at higher doses. It is important to note that >75 μm fraction constituted only about 5% of the total particles count in the secondary effluent.

The above findings highlight the inverse relationship between UV disinfectability and floc size. Similar conclusions were drawn in recent studies carried out by Yong et al. (2008) and Azimi et al. (2012). This result has important practical implications since it can be used to better optimize the upstream processes for enhancing UV disinfection of effluent (Jolis et al. 1999; Loge et al. 2001). This finding, however, undermines earlier suggestions that all flocs greater than 10 μm provide equal UV shielding for their embedded coliform bacteria (Emerick et al. 1999, 2000; Jolis et al. 1999; Loge et al. 1999).

### The effect of floc size on UV resistance and tailing propensity

Table 1 shows the average value of P obtained using Equation (2) for various activated sludge floc size fractions. The percentage of viable flocs varied by nearly four times from about 5% for the smallest size fraction to 22% for the largest one. Larger flocs have a greater volume of biomass and hence the probability of finding a culturable fecal coliform if higher (i.e. greater P). Between the 20–25 μm and 32–45 μm size fractions, no significant difference was detected in the cultivable floc fraction (p-value = 0.12). However, significant differences in the cultivable floc fraction were detected when comparing the 32–45 μm with 53–63 μm (p-value = 0.04), 53–65 μm with 90–106 μm (p-value = 0.008), and 90–106 μm with 125–150 μm (p-value 0.001) fractions.

![Figure 3](image-url)  
Figure 3: Calculated contribution of various floc size fractions to the surviving CFUs in the UV disinfection of activated sludge effluent.

Values of k₁, k₂, and β for various floc size fractions examined in this work are given in Table 1. As expected, by increasing floc size, the tailing level, β, of the UV DRC increased. The initial slope, k₁, also showed a decreasing trend when changing the size fraction from 32–45 μm to 53–63 μm (p-value = 0.002). The slope of tailing region, k₂, however, did not change significantly with floc size (p-value = 0.54). While these results are consistent with our earlier findings (Azimi et al. 2012), they are contrary to an earlier study by Bohrerova & Linden (2006) that reported similarities in the initial slope of UV DRC for filtered and unfiltered effluents. In the latter study, however, samples contained a large concentration of free microbes and the initial slope, k₁, was controlled by the inactivation of these microbes and remained the same for filtered and unfiltered samples. In our work, as a result of sieving, free microbes were not present in the fractionated floc samples, and hence k₁ was sensitive to floc characteristics. Table 1 also shows that the main inactivation slope (kᵰ) decreased somewhere between 45 and 53 μm. This is likely because flocs larger than 40 μm are likely to contain dense cores (Azimi et al. 2012, 2013) that have been shown to create resistance to UV inactivation by harboring fecal coliforms and reduce the observed initial slope of UV DRC. These findings further support the significance of the contribution of various floc size fractions to the UV disinfection of final effluent, as previously demonstrated in Figure 3.

Here, we use parameter β to estimate tailing propensity, TP. Values of TP for the various size fractions, calculated according to Equation (4), are shown in Figure 4. TP for the smallest size fraction was about 0.0019, while that of the largest size fraction was about 0.064. Hence, flocs larger than 125 μm were about 35 times more likely to have a high degree of resistance to UV disinfection than those in the 20–25 μm size fraction. Since most wastewater flocs (by number) were smaller than 25 μm, the small TP

### Table 1 | UV disinfection model parameters for various activated sludge floc size fractions

<table>
<thead>
<tr>
<th>Size fraction (μm)</th>
<th>β</th>
<th>k₁ (cm²/mJ)</th>
<th>k₂ (cm²/mJ)</th>
<th>P (CFU/particle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–25</td>
<td>0.034</td>
<td>0.174 ± 0.036</td>
<td>0.033 ± 0.010</td>
<td>0.054</td>
</tr>
<tr>
<td>32–45</td>
<td>0.043 ± 0.019</td>
<td>0.177 ± 0.019</td>
<td>0.032 ± 0.003</td>
<td>0.055 ± 0.023</td>
</tr>
<tr>
<td>53–63</td>
<td>0.078 ± 0.037</td>
<td>0.119 ± 0.020</td>
<td>0.029 ± 0.002</td>
<td>0.061 ± 0.029</td>
</tr>
<tr>
<td>90–106</td>
<td>0.163 ± 0.056</td>
<td>0.111 ± 0.015</td>
<td>0.031 ± 0.005</td>
<td>0.222 ± 0.078</td>
</tr>
<tr>
<td>125–150</td>
<td>0.295</td>
<td>0.107 ± 0.027</td>
<td>0.027 ± 0.218</td>
<td>0.218</td>
</tr>
</tbody>
</table>

The ± values represent 90% confidence intervals.  
*Confidence intervals could not be reliably estimated due to insufficient number of replicates.
value of this fraction suggests that most wastewater flocs were not culturable and/or were not UV-resistant.

**Trickling filter versus activated sludge UV disinfection**

PSD and UV DRC of trickling filter and activated sludge effluents are presented in Figures 5 and 6, respectively.

Based on Figure 5, the total particle count in the trickling filter effluent was almost double that of the activated sludge sample for flocs smaller than 50 μm (corrected particle size). This caused a higher effluent suspended solids and a lower UVT in the final effluent of the trickling filter process compared to the activated sludge sample (22 ± 5 mg/L vs. 9 ± 5 mg/L, and UVT of 60 ± 5% vs. 70 ± 5%). In addition, based on Figure 6(a) the CFU count (/100 mL) of the trickling filter sample at UV doses of zero and 10 mJ/cm² were about 0.8 log and 1.5 log higher than those of the activated sludge sample, respectively. This result suggests that the presence of a larger number of free microbes or small flocs that, as mentioned previously, are the main contributors to the CFU count at low UV doses. More importantly, the tailing level of the trickling filter effluent was found to be about 2 log larger than that of the activated sludge sample (Figure 6(a)). Since the number concentration of flocs larger than 50 μm (corrected particle size) was nearly identical, the difference in the tailing level of the two effluents was likely indicative of a larger concentration of UV-resistant flocs in the trickling filter sample.

To further examine the origin of differences in the UV inactivation of activated sludge and trickling filter effluent samples, the UV DRC model parameters for various floc size fractions obtained from the trickling filter process are listed in Table 2. Based on this table, slope of the tailing region, k₂, was not sensitive to changes in the floc size nor changing the process from activated sludge to trickling filter. Compared to similar size activated sludge flocs (Table 1), a larger fraction of trickling filter flocs were found to be UV-resistant (i.e. large β). This

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>32–45 μm</th>
<th>53–63 μm</th>
<th>90–106 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>k₁</td>
<td>0.15 ± 0.02</td>
<td>0.10 ± 0.02</td>
<td>0.09 ± 0.03</td>
</tr>
<tr>
<td>k₂</td>
<td>0.03 ± 0.003</td>
<td>0.03 ± 0.005</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>β</td>
<td>0.06 ± 0.02</td>
<td>0.13 ± 0.03</td>
<td>0.40 ± 0.03</td>
</tr>
<tr>
<td>P</td>
<td>0.12 ± 0.02</td>
<td>0.19 ± 0.03</td>
<td>0.68 ± 0.05</td>
</tr>
</tbody>
</table>

The ± values represent 90% confidence intervals.
result is supported by the higher tailing level of UV DRC of trickling filter sample compared to that of the activated sludge sample, as seen in Figure 6(b).

Moreover, with increasing the floc size from 32–45 μm to 90–106 μm fraction, P for the activated sludge and trickling filter flocs varied between 5–29% and 12–68%, respectively. For comparison, following a similar procedure, Farnood (2004) reported P to be within 7–11% while Emerick et al. (1999) reported a range of 5.8–31.1% using fluorescence in-situ hybridization technique. Given the relatively small value of P for small flocs (i.e. 5–12%), it can be concluded that most suspended flocs in the activated sludge samples were not culturable. This is in agreement with the observation made by Qualls et al. (1985) that many of the small particles did not contain coliform bacteria. These results also show that size had a strong influence on the culturability of wastewater flocs: the culturability of the largest size fraction for both TF and AS samples was almost 6 times that of the smallest fraction in this study. This is expected, given that larger flocs had a larger volume and were therefore more likely to contain culturable fecal coliform bacteria. It is important to notice that within a fixed size fraction, the value of P for trickling filter flocs was 2 to 3 times greater than that of activated sludge flocs (see Tables 1 and 2). Given the higher P and β values for trickling filter flocs, they had a higher tailing propensity than the same size activated sludge flocs (see Figures 4 and 7).

According to Equation (2), the higher P value of flocs combined with the higher particle concentration in the trickling filter sample (see Figure 5) is expected to result in a greater initial count (N₀) for this sample compared to the activated sludge sample. In addition, since β is also higher for trickling filter flocs, and given that the fraction of particles that contribute to the tailing level is given by p β N₀ (as per Equation (5)), the tailing level of trickling filter effluent sample is expected to be much higher than that of the activated sludge sample. These conclusions are consistent with the results presented in Figure 6(a) where N₀ and tailing level for trickling filter effluent were about 0.8 log and 2 log higher than those of the activated sludge sample.

As seen in Figure 7, as many as a quarter of all 90–106 μm trickling filter flocs contributed to the tailing of UV DRC. Moreover, TP values of the trickling filter flocs were 3 to 8 times greater than that of the activated sludge, and this difference was larger as floc size increased. As the number concentration of large flocs (>50 μm) in the two effluent samples were similar, hence the poor disinfection performance of trickling filter effluents can be explained based on their higher TP values.

Estimating UV DRC based on effluent PSD

In this section, the application of the proposed model for predicting the disinfection performance of effluents based on their PSD is demonstrated. PSD of the activated sludge sample used in this study is provided in Figure 8(a). This PSD was divided into six regions each corresponding to one of the floc size fraction as per Table 3. The particle count in each size range, Nₚ, was determined and the model parameters for various activated sludge floc size fractions, as given in Table 1, were assigned to their corresponding particle size range. Flocs smaller than 20 μm were
considered to follow inactivation of free floating fecal coliforms, hence values of \( k \) and \( \beta \) for this size fraction were assigned to be 0.349 mJ/cm\(^2\) and 0, respectively. Moreover, the fraction of culturable flocs, \( P \), for these flocs was determined experimentally to be 0.68. The above parameters were then used to predict the disinfection performance of the activated sludge effluent sample according to the mathematical model presented by Equation (6). Figure 8(b) shows that the estimated CFUs were between 0.07 to 0.34 log (on average \( \frac{1}{4} \) log) above the experimental values. Although the predicted UV DRC was systematically above the actual data, the error was within the range of variability of the model parameter.

The above analysis illustrates the utility of the methodology presented in this manuscript for estimating the effect of particle associated coliforms on the tailing of the UV DRC. The goodness of model predictions was further examined by comparing the predicted versus actual UV DRCs for all effluent samples resulting in an R-square value of 0.86 (not shown here). This finding suggests that for a given wastewater treatment plant, the daily fluctuations in influent quality and operating conditions of the wastewater treatment plant had little effect on the UV disinfection kinetics of individual floc size fractions but depend on the process type. Furthermore, any major changes or upset in the secondary treatment plant operation or influent quality is expected to alter the UV inactivation kinetics of wastewater flocs.

### CONCLUSIONS

UV DRC of secondary effluents not only depends on the concentration but also on the tailing propensity of suspended particles. Tailing propensity captures the overall effects of floc culturability and UV resistance on the UV disinfection kinetics. It was shown that having a higher culturability and larger UV-resistance, larger flocs had a much greater impact on the tailing of UV DRC. Activated sludge flocs larger than 125 \( \mu m \) exhibited as much as 35 times greater tailing propensity than those in the size range of 20–25 \( \mu m \); a consequence of the combination of having a greater tendency of harboring coliform bacteria and greater fraction of UV-resistant compact regions. Tailing propensity was also found to depend on the wastewater treatment process. Flocs formed in the trickling filter process were found to have significantly higher tailing propensity values compared to those from the activated sludge process. A much greater percentage of trickling filter flocs were culturable in all of the size fractions. This, combined with higher concentration of flocs in the sample, caused poorer UV disinfection performance of the trickling filter effluent. The tailing level of the trickling filter sample examined in this work was 2 log higher than that of the activated sludge sample, despite having similar number of flocs greater than 50 \( \mu m \). Finally, a mathematical model was presented in this study that can be used to estimate the UV DRC of effluents in measuring the size distribution of effluent suspended particles. However, such a model is process-specific and likely requires recalibration for any major changes in the influent conditions or wastewater treatment plant operation.

### ACKNOWLEDGEMENTS

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### REFERENCES

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**Table 3** Particle concentration for various particle size fractions in the activated sludge sample in Figure 8

<table>
<thead>
<tr>
<th>Floc size fraction (( \mu m ))</th>
<th>Particle size range (( \mu m ))</th>
<th>Coulter particle size range (( \mu m ))</th>
<th>Particle count (#/10 mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>&lt;17</td>
<td>&lt;7.9</td>
<td>14,000</td>
</tr>
<tr>
<td>20–25</td>
<td>17–28</td>
<td>7.9–13.1</td>
<td>10,700</td>
</tr>
<tr>
<td>32–45</td>
<td>28–49</td>
<td>13.1–22.9</td>
<td>6,000</td>
</tr>
<tr>
<td>53–63</td>
<td>49–76</td>
<td>22.9–35.1</td>
<td>2,300</td>
</tr>
<tr>
<td>90–106</td>
<td>76–116</td>
<td>35.1–54.2</td>
<td>650</td>
</tr>
<tr>
<td>&gt;106</td>
<td>&gt;116</td>
<td>&gt;54.2</td>
<td>110</td>
</tr>
</tbody>
</table>

Coulter particle size range was determined based on Equation (7).


Kachel, V. 1986 Investigations into Coulter sizing of biological particles; theoretical background and instrumental improvements. Part. Part. Syst. Char. 3 (2), 45–53.


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