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Impact of suspended particles on UV disinfection of activated-sludge effluent with the aim of reclamation

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A B S T R A C T

Ultraviolet (UV) disinfection is now widely implemented as a tertiary treatment for wastewater reclamation. The negative impact of suspended particles on UV disinfection efficiency has been established. The aim of this study was to provide plant operators with a simple way to predict water quality degradation. To this end, simple correlations between indicators of suspended particles contamination and UV disinfection efficiency of activated-sludge effluents were explored using effluents from a wastewater treatment plant (WWTP) in the South of France. Three groups of microorganisms were considered: coliforms, *Escherichia coli* and enterococci. To test activated-sludge effluents of varying quality, secondary effluent was blended with different volumes of mixed liquor from the aeration tank of the WWTP. The number of particles greater than 25 µm was found to be well-correlated with total suspended solids (TSS) ($R^2 = 0.88$), turbidity ($R^2 = 0.94$) and UV transmittance at 254 nm ($UV_{T_{254}}$) ($R^2 = 0.81$). Large particles were shown to impact UV disinfection at two main levels: they scattered UV light and they shielded bacteria inside their compact cores. Linear correlations were determined in this study between indicators of suspended particles presence and 1) inactivation constant of the UV-susceptible fraction of the microorganisms studied, 2) residual bacterial counts after exposition to high UV fluence (tailing potential). These correlations are intended to be used by the wastewater reclamation plant operator to predict the effect of secondary effluent quality degradation on the UV disinfection treatment process.

Keywords:

Wastewater reuse
UV disinfection
Suspended particles
Tailing

1. Introduction

Increasing water stress is likely to occur due to population growth, industrialization, agricultural practices, urbanization and climate change. In Southern Europe, for instance, it is frequent to face water restrictions during summer, especially in touristic areas in order to preserve the resource for potable use at the expense of recreational or even agricultural uses. In parallel, an increase of wastewater generation is observed due to both an increase in population and an increase of water use per person. Wastewater reuse, defined as the use of treated municipal wastewater (reclaimed water), may be one of the appropriate responses to face global freshwater scarcity [1].

In order to use reclaimed water for urban or agricultural purposes, the quality of activated-sludge secondary effluents is generally acceptable regarding to physicochemical indicators, but a disinfection step is needed to remove microorganisms, considering that some of them

might be pathogenic for humans, domestic animals or crops. Ultraviolet (UV) disinfection is now widely implemented as a tertiary treatment for wastewater reclamation. Indeed, it is a robust and economically viable technology, and it satisfactorily addresses two significant concerns about chlorination: the formation of toxic by-products and the low removal of protozoa as *Cryptosporidium* [2].

Since the use of the provided water may have a direct impact on human health, a continuous monitoring of the production process reliability is crucial. The main indicator recommended is *Escherichia coli* and other pathogens, faecal indicator bacteria or pathogen surrogates [3–5]. Several guidelines and regulations concerning reclaimed water reuse have been adopted in the last years, for agricultural or other uses. Each text has its own indicators and quality thresholds [3]. French regulations define four quality levels depending of the use of reclaimed water considered. The highest quality level applies to irrigation of all types of crops and unrestricted urban areas. Four microbial indicators

Abbreviations: BOD₅, biological oxygen demand (5 days); CFU, Colony Forming Unit; k₁, inactivation constant of UV-susceptible microorganisms; k₂, inactivation constant of microorganisms shielded from UV light; MPN, Most Probable Number; PSD, particle size distribution; REF, reduction equivalent fluence; Res₄₀, residual colony count after exposition to a REF of 40 mJ/cm²; TSS, total suspended solids; UV, Ultraviolet; $UV_{T_{254}}$, UV transmittance (10 mm path length) at 254 nm; WWTP, wastewater treatment plant

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are used: *E. coli* (maximal count in treated water: 250 CFU/100 mL), faecal enterococci, F-RNA coliphages and sulfito-reducing bacteria (minimal log removal: 4 log) [6]. In our study, the microorganisms studied were: *E. coli*, total coliforms and enterococci, considering that the combination of these indicators is sufficiently representative of pathogen contamination risk [4].

The impact of suspended particles on UV disinfection efficiency has been established and well-documented [7–9]. Particles can diffuse light and reduce UV transmittance of water. Microorganisms can even be embedded in the particulate matter [7,9]. Particle-microorganism association is regulated by the double layer theory [10] stating that attraction operates at two levels around the particle: the “secondary energy zone” (5–10 nm of the particle surface) where the attraction is reversible; and the “primary energy zone” (1 nm of the particle surface) where the attraction is irreversible. This mechanism is influenced by several factors, the principal one being the particle size. Bacteria are usually associated with particles larger than 10 µm [9], while viruses may be associated with smaller particles (less than 2 µm) [11]. Recent works demonstrated that UV disinfection efficiency may be influenced by the great variability of biofloc size and structure found in secondary effluents. Large and compact flocs have a stronger tendency to shield coliform bacteria [12,13].

The aim of this study was to provide plant operators with a decision tool to adjust or to shutdown the water reclamation process. Such tool should be easy to operate and able to give quick (ideally immediate) results. To that aim, we have chosen to determine correlations between indicators such as turbidity, total suspended solids (TSS) and UV transmittance at 254 nm (UVT₂₅₄), and UV disinfection efficiency of activated-sludge effluents, as well as to evaluate the influence of such parameters on inactivation constants and tailing. These parameters are of key importance for dimensioning of UV disinfection and real time risk control during reused water production.

2. Material and methods

2.1. UV reactor description

The 50 L UV batch experimental reactor used in this study was a cylindrical reactor made in stainless steel (Fig. 1). The following elements were included:

- low-pressure UV lamp of 6 W (TUV 6WGST5, Philips, Germany) with an electronic ballast (Delta UV, USA),
- UV intensity sensor (D-SICONORM, ZED, Germany) to monitor lamp aging and/or fouling,

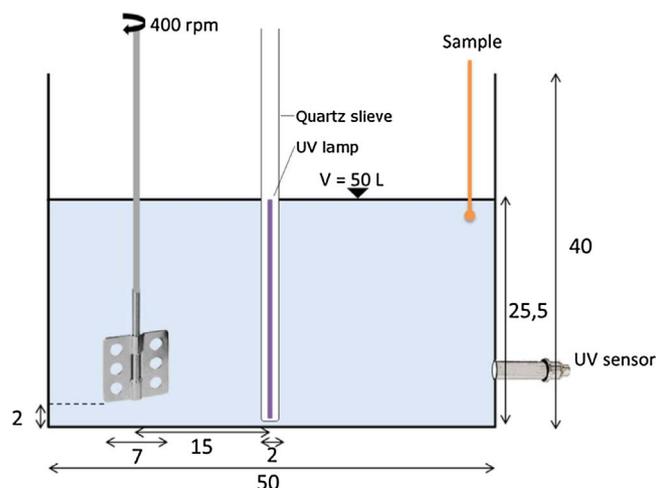


Fig. 1. Schematic description of the experimental UV reactor used in this study (sectional view). All dimensions are given in centimeters.

- overhead stirrer (Hei-TORQUE Value 200, Heidolph, Germany) with a blade impeller (R1375, IKA, Germany). The mixing speed was set up at 400 rpm. The mixing conditions were designed to ensure homogenization in 30 s without affecting microorganisms.

2.2. Determination of reduction equivalent fluences (REF) applied in the reactor

For a given volume of water to be treated, the applied UV fluence is defined as the product of the mean fluence rate and the exposure time as shown in Eq. (1):

$$F = E_{avg} \times t \quad (1)$$

where F is the applied fluence (J/m^2), E_{avg} is the mean fluence rate (W/m^2) defined as the total radiant power incident from all directions onto an infinitesimally small sphere and t is the contact time (in seconds) [14]. The determination of applied UV fluence in a reactor is complex because fluence rate is not uniform throughout the system [15]. In order to determine an equivalent fluence, biodosimetry is based on the use of a microorganism with calibrated UV inactivation response assessed with collimated beam reactor experiments [14]. The inactivation observed through the UV disinfection system is compared to the calibrated UV inactivation response to establish an equivalence called reduction equivalent fluence (REF). This procedure of REF determination is recognized as one of the most accurate to assess the UV fluence applied in a reactor [15].

In our study, the microorganism chosen for REF determination was *Escherichia coli* ATCC 15597. The first step was to determine its UV inactivation constant. For this purpose, an overnight culture of *E. coli* ATCC 15597 was placed in incubation in Luria liquid broth (CONDA Microbiology, Spain) at 37 °C during two to four hours in order to reach exponential growth phase (absorbance at 600 nm above 1). This culture (about 10^6 CFU/mL) was diluted in tap water in order to reach an UVT₂₅₄ between 60 and 70%. Small volumes (15 mL) of this culture were then exposed to UV fluences from 0 to 15 mJ/cm^2 with a collimated beam apparatus (Atlantium, Israël), in accordance with Bolton et al. prescriptions [14]. This apparatus contained a low-pressure UV lamp of 15 W (TUV 6WGST5, Philips, Germany) and irradiance measures were made with a portable radiometer (MS-100, UVP, Canada). The collimated beam experiments were repeated three times.

Inactivation was calculated by comparing *E. coli* ATCC 15597 colony formation before and after UV irradiation. Bacterial colony counts were performed by culture of 1 mL sample (after dilution if required) in ready-to-use plates containing a dehydrated medium specific to *E. coli* (Compact Dry EC, HyServe, Germany). Colony Forming Units (CFU) per mL were enumerated after 24 h incubation at 37 °C. The inactivation constant of *E. coli* ATCC 15597 was calculated with Eq. (2):

$$\log_{10}\left(\frac{N_D}{N_0}\right) = -k \cdot F \quad (2)$$

where N_0 and N_F are the *E. coli* ATCC 15597 colony counts (CFU/mL) respectively before and after application of the UV fluence F (mJ/cm^2) and k is the inactivation constant (cm^2/mJ).

The determination of REF in the UV reactor was based on the same indicator microorganism. A culture of *E. coli* ATCC 15597 was prepared as previously described and placed in the reactor. The timer was started when the UV lamp was switched on. Sampling and culture procedure were the same as for collimated beam experiments. Inactivation after a given exposure time was converted into REF with Eq. (2). This experiment was repeated four times.

2.3. UV disinfection experiments

UV disinfection experiments were performed with effluents from a wastewater treatment plant (WWTP) in the South of France. This

Table 1

Range of values observed for water quality parameters measured on the activated-sludge effluents used for UV disinfection experiments (12 experiments).

| Water quality parameter | Unit | Range of values |
|---|------------------------------|-----------------|
| TSS | mg/L | 0.8–73.3 |
| Turbidity | NTU | 0.6–23.3 |
| Unfiltered UVT ₂₅₄ | % (10 mm path length) | 57.0–71.6 |
| Filtered UVT ₂₅₄ | % (10 mm path length) | 70.2–71.2 |
| Unfiltered iron | mg/L | 0.05–0.66 |
| Filtered iron | mg/L | 0.05–0.07 |
| Total coliforms | log ₁₀ MPN/100 mL | 4.8–5.5 |
| <i>E. coli</i> | log ₁₀ MPN/100 mL | 3.9–4.8 |
| Enterococci | log ₁₀ MPN/100 mL | 2.9–4.5 |
| Particle size distribution (size class in μm) | | |
| Total (> 2 μm) | N/mL | 1636–5803 |
| [2–5] | N/mL | 950–1954 |
| [5–25] | N/mL | 440–2696 |
| > 25 | N/mL | 43–1961 |

WWTP was based on a conventional biological process scheme and treated mainly domestic wastewaters. The pre-treatment consisted on grids to eliminate macro wastes and on removal of grease and sands by primary clarifiers. Secondary treatment was performed by activated sludge, with advanced treatment of nitrogen (nitrification, denitrification) and phosphorus (chemical precipitation) removal. The daily production of secondary effluent was 28,000 m³/day with an organic charge corresponding to 230,000 person equivalent (p.e.) (considering 60 g BOD₅/p.e./day). The quality of the secondary effluent (annual mean) was characterized by low amounts of nitrogen (4–5 mg/L), phosphorus (0.8 mg/L) and suspended solids (< 10 mg/L). No significant seasonal change was observed in the previous three years.

To test activated-sludge effluents of varying quality, secondary effluents were blended with different volumes of mixed liquor from the aeration tank of the WWTP. This liquor had total suspended solids content between 3.5 and 5 g/L. Hence a wide range of activated-sludge effluent quality was tested as summarized in Table 1 (12 experiments).

For each experiment, secondary effluent and liquor were collected at the WWTP and transported to the laboratory intending to be processed within three hours. After proper mixing in the 50 L reactor, the following analyzes were conducted before UV irradiation:

- TSS according to the NF EN 872 standard [16],
- turbidity with a portable turbidimeter (HI 98703, Hanna instruments, USA),
- UVT₂₅₄ with a spectrophotometer (Anthélie, Secomam, France) and a quartz cell of 10 mm path length,
- total iron content with the FerroZine method (Hach Lange, USA) and a portable spectrometer (DR890, Hach Lange, USA),
- particle size distribution (PSD) with a particle counter (ARTI WPC-22, Hach Lange, USA) on the basis of light blocking,
- UVT₂₅₄ and iron content were also measured on the dissolved fraction after filtration with a syringe filter (PVDF) of 0.45 μm pore size (Millex HV, Millipore, USA).

All these measurements were performed in triplicate for each experiment.

Three groups of microorganisms were studied: *E. coli*, total coliforms and enterococci. Bacterial counts were based on Most Probable Number (MPN) determination. One hundred mL samples were made in the UV reactor with a sterile pipette, stored in the dark at 4 °C and processed within two hours. Specific liquid culture media were used: Colilert-18 for *E. coli* and coliforms, and Enterolert-E for enterococci (IDEXX, USA). Quantification was made after 18–22 h incubation at 37 °C (Colilert) or 24 h incubation at 41 °C (Enterolert) by counting positive wells in a tray containing two serial dilutions (Quanti-Tray 2000, IDEXX, USA). Results were expressed in log₁₀ MPN per 100 mL.

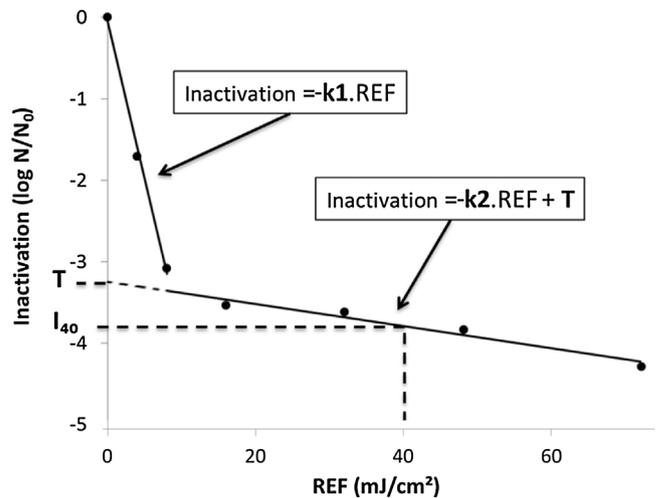


Fig. 2. Expected UV response model of the microorganisms studied in the presence of particles (T: tailing threshold; REF: reduction equivalent fluence).

Inactivation was determined by comparing microorganism MPN before turning on the UV lamp and after exposure to a given fluence.

2.4. UV disinfection model in the presence of suspended particles

In the presence of suspended particles, the first order disinfection model (Eq. (2)) is no longer valid: the inactivation constant is very low for high REF. This phenomenon is due to the fraction of microorganisms shielded from UV irradiation and it is called tailing [7,9]. The UV response of microorganisms in the presence of particles can be described by combining the response of UV-susceptible (or 'free') microorganisms and the response of microorganisms shielded from UV. The following constants were determined (Fig. 2):

- k_1 : inactivation constant of UV-susceptible microorganisms
- k_2 : inactivation constant of microorganisms shielded from UV light
- Tailing threshold (T)
- Res_{40} : residual colony count after exposition to a REF of 40 mJ/cm². For the microorganisms studied, a REF of 20 mJ/cm² was considered as sufficient to obtain a maximal inactivation (> 7 log) in pure water [17]. In the presence of particles in suspension, the fraction of these microorganisms which are resistant to a REF of 40 mJ/cm² was thus considered as shielded from UV light and responsible for tailing. If I_{40} is the inactivation measured after application of 40 mJ/cm² UV, then $Res_{40} = \log N_0 + I_{40}$

2.5. Statistics

Data processing and statistics were done with Excel 2010 (Microsoft, USA) and with XLSTAT Base v18.07 (Addinsoft, France). Significant differences between datasets were deemed by non-parametric tests: Wilcoxon signed rank test for paired datasets and Mann-Whitney's test for independent datasets. An alpha level of 0.05 was chosen as a threshold for significance. Linear regression was used to assess the strength of the relationship between two variables.

3. Results and discussion

3.1. Inactivation constant of *E. coli* ATCC 15597 and REF determination

The inactivation level of *E. coli* ATCC 15597 as a function of the UV fluence applied in the collimated beam reactor is presented in Fig. 3. As *E. coli* is known to be sensitive to UV irradiation, the inactivation constant was determined for UV fluences lower or equal to 15 mJ/cm², in agreement with Hijnen et al. [17]. The constant is given by the slope

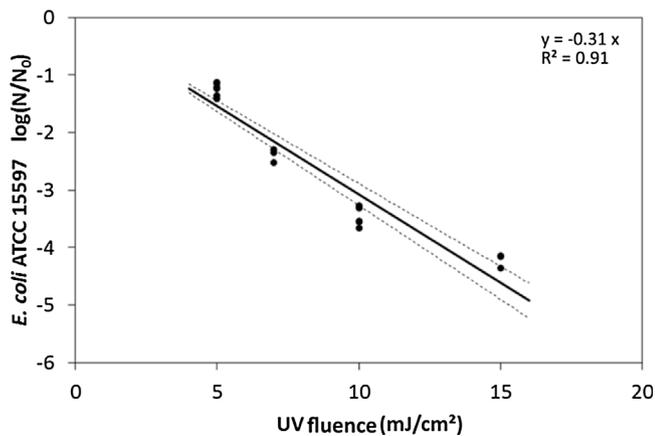


Fig. 3. Calibrated UV fluence – inactivation response for *E. coli* ATCC 15597 measured with the collimated beam reactor. Dotted lines represent the 95% confidence interval of the regression (initial *E. coli* content was about 10^6 CFU/mL and UV fluences applied between 0 and 15 mJ/cm^2).

value of the linear regression between UV fluence and inactivation data. It is independent of the water characteristics (in a given range of application, typically $\text{UVT}_{254} > 60\%$), as correction factors are applied during collimated beam experiments [14].

For *E. coli* ATCC 15597 in our study, the inactivation constant value was $0.31 \pm 0.02 \text{ cm}^2/\text{mJ}$ ($R^2 = 0.91$). This value is in accordance with data found in the literature for various *E. coli* strains, with inactivation constant values between 0.3 and $0.6 \text{ cm}^2/\text{mJ}$ [17–19]. This experimental value was used to determine REF in the experimental UV reactor.

Inactivation of *E. coli* ATCC 15597 in the experimental UV reactor was conducted with pure cultures diluted in tap water to obtain a volume of 50 L. UVT_{254} values measured on diluted cultures for the four replicates were 64.8, 67.1, 67.9 and 68.6% respectively. The inactivation kinetics were not significantly different between the four replicates (Wilcoxon signed rank test, $p > 0.05$). Contrary to the collimated beam reactor, it was not possible to apply correction factors depending to water characteristics. Hence, the REF determined in the experimental reactor must be expressed in mJ/cm^2 equivalent for UVT_{254} of $67 \pm 2\%$ (10 mm path length). UV exposure times applied in the reactor (0–90 min) corresponded to REF between 0 and 110 mJ/cm^2 with a coefficient of variation of 10% (based on the four replicates). REF above 15 mJ/cm^2 (corresponding to the total inactivation of *E. coli* ATCC 15597) were extrapolated on a linear basis.

3.2. Secondary effluents characterization

The range of values observed for water quality parameters measured on the activated-sludge effluents used for UV disinfection experiments are presented in Table 1. The secondary effluent at the outlet of the WWTP was characterized by a TSS content around 2 mg/L , which is low in comparison with the quality threshold of 15 mg/L TSS defined by French regulations for the use of reclaimed water for irrigation of all types of crops and unrestricted urban areas [6]. This was confirmed by turbidity values under 1 NTU and UVT_{254} values around 70 % (Table 1).

The blending of mixed liquor from the aeration tank to the secondary effluent led to an increase of the particulate content. More precisely, liquor addition consisted on an input of large particles with an equivalent diameter above $25 \mu\text{m}$ (Table 1 and Fig. 4). Indeed the content of particle of this size class was well-correlated with TSS ($R^2 = 0.88$), turbidity ($R^2 = 0.94$) and UVT_{254} ($R^2 = 0.81$). UVT_{254} of the filtered samples did not vary with liquor addition, meaning that no significant amount of dissolved organic matter was brought by the liquor.

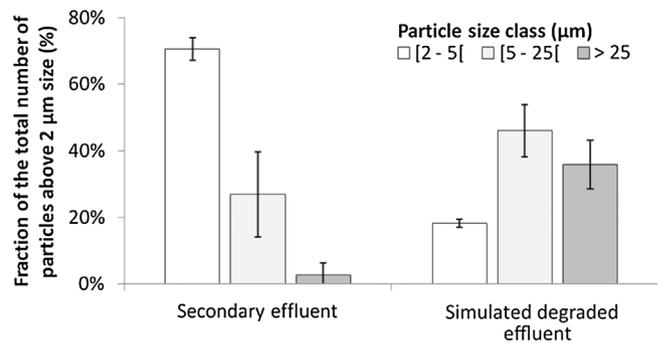


Fig. 4. Influence of mixed liquor addition on the particle size distribution of the secondary effluent.

There was a significant input of iron consecutive to liquor addition, but in its particulate form since the filtered iron content remained stable (Table 1). Even if these particulate forms have an impact on UV disinfection due to scattering, they are less susceptible to absorb UV light than dissolved forms of iron [20].

The blending procedure implemented in this study between the mixed liquor and the secondary effluent of the WWTP may be representative of a dysfunction on the treatment process. For instance, it may correspond to a lack of aeration or another perturbation of the biological balance in the aerated tank, which impacts the clarification step (bulking or foaming phenomena) and leads to the release of large particles at the outlet of the WWTP [21].

3.3. Impact of suspended particles on disinfection of UV-susceptible microorganisms

Inactivation of UV-susceptible microorganisms can be modeled by the inactivation constant k_1 (Fig. 2). For all the effluents studied, k_1 values for *E. coli* and for the coliforms were not significantly different (Wilcoxon signed rank test, $p > 0.05$). Considering the secondary effluent without addition of mixed liquor, observed mean k_1 values were $0.29 \text{ cm}^2/\text{mJ}$ for *E. coli*/coliforms and $0.16 \text{ cm}^2/\text{mJ}$ for enterococci. These values were in accordance with literature data for environmental strains [17,22,23].

Addition of mixed liquor in the secondary effluent (measured by a decrease of UVT_{254}) resulted in decrease of k_1 values. A strong correlation ($R^2 > 0.75$) was established between the inactivation constant of UV-susceptible *E. coli*/coliforms and enterococci, and bulk indicators of suspended particles presence such as UVT_{254} (Fig. 5), turbidity or TSS. This increase of UV resistance related to the presence of particles was due to two main factors: UV light scattering by the particles and association of particles with bacteria [10,17,24]. Absorption of UV irradiation by aromatic compounds at the surface of the flocs may also occurred [25].

Particle size seems to be decisive to induce the shading of microorganisms. Madge & Jensen [8] observed that k_1 inactivation constant of fecal coliforms associated with large particles (size above $20 \mu\text{m}$) was significantly lower than for fecal coliforms associated with small flocs (size under $5 \mu\text{m}$). Concerning microorganisms embedded in particles, Azimi et al. [26] established that liquor flocs are composed of an easily disinfectable loose outer shell, and a physically stronger compact core inside. They showed that k_1 decreased significantly with increasing floc size and they hypothesized that this was due to the higher proportion on compact cores in bioflocs which reduces the UV penetration and hence increases the resistance to UV disinfection [26].

Industrial UV reactors are designed based on reduction equivalent fluence (REF) determination through biodosimetry measurements. In our study REF were determined for a given water quality (UVT_{254} of $67 \pm 2\%$). To account for higher UV resistance (decrease of k_1) due to degraded water quality, a correction factor has to be applied to the REF

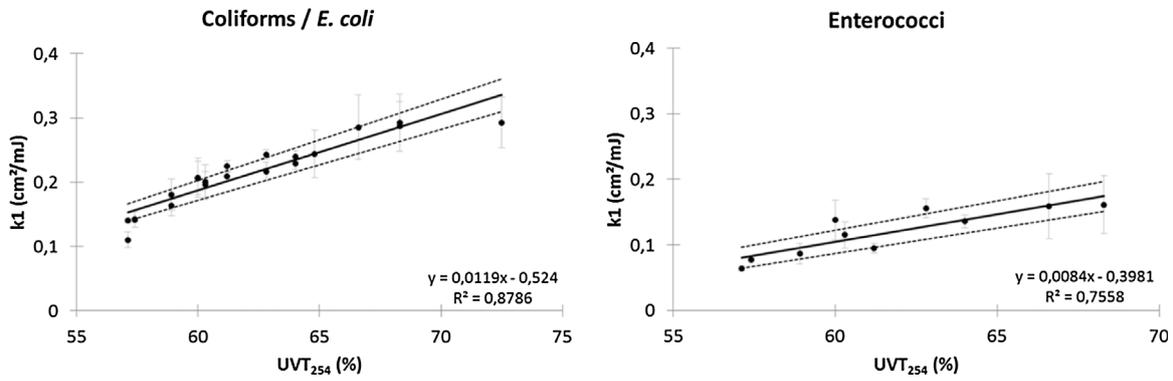


Fig. 5. Linear regressions (dotted lines represent the 95% confidence interval) between UVT_{254} and the inactivation constant of UV-susceptible coliforms/*E. coli* and enterococci. Depicted bars represent standard deviation (negligible for UVT_{254}).

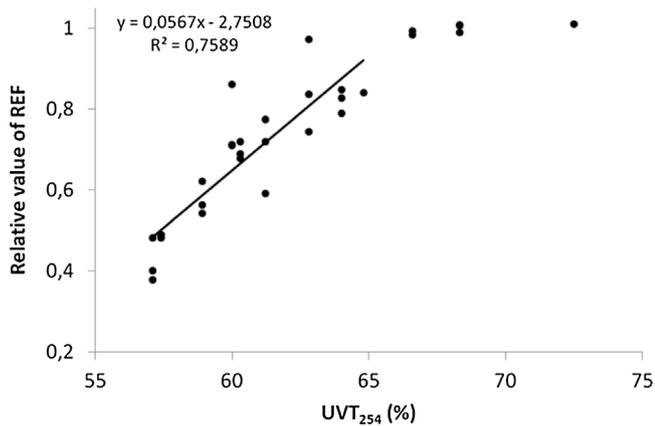


Fig. 6. Relative value of REF as a function of UVT_{254} in activated-sludge effluents of varying quality from the WWTP studied. Data for coliforms/*E. coli* and for enterococci are gathered.

in order to estimate real UV fluences applied to the microorganisms when UVT_{254} decreases [26]. This factor is directly proportional to the decrease of k_1 . Based on Eq. (2) and on the slopes of the linear correlations presented in Fig. 5 it was possible to determine the relative value of REF as a function of UVT_{254} (Fig. 6). Data for coliforms/*E. coli* and for enterococci were gathered because no significant difference was observed between the slopes of the linear correlations presented in Fig. 5 (Wilcoxon signed rank test, $p = 0.75$). The empirical relationship presented in Fig. 6 may be useful to adjust the UV fluence applied in the reactor with the aim to maintain the REF defined by increasing UV lamps intensity.

3.4. Impact of suspended particles on disinfection of microorganisms shielded from UV light

The fraction of coliforms and enterococci resistant to a REF of 40 mJ/cm^2 was considered to be shielded from UV light and responsible for tailing. Spontaneous repair of UV-damaged cells can occur, but this phenomenon is considered as negligible in the dark [27]. Considering the secondary effluent without addition of mixed liquor, no residual *E. coli* colony count was observed after application of a REF of 40 mJ/cm^2 . Conversely, significant tailing was observed for coliforms and enterococci, with Res_{40} mean values of 6 and 2 MPN/100 mL respectively (Fig. 7).

In secondary effluents, *E. coli* is mainly in the form of dispersed mobile cells which are not prone to aggregation with particles [9]. However, it was observed that coliforms have an ability of self-aggregation when cell density increases and in reaction to the stress induced by UV irradiation [28]. In our study, this phenomenon was not observed in the secondary effluent, but it might be the case for other

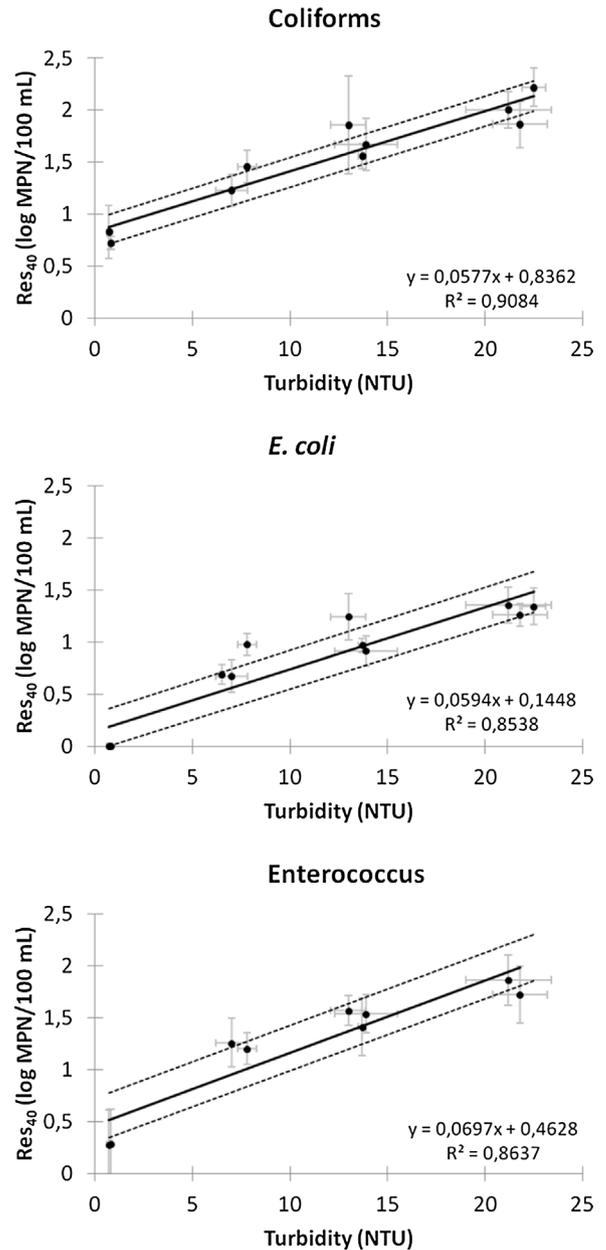


Fig. 7. Linear regressions (dotted lines represent the 95% confidence interval) between turbidity and Res_{40} (residual colony count after exposure to a REF of 40 mJ/cm^2) for coliforms, *E. coli* and enterococci. Depicted bars represent standard deviation.

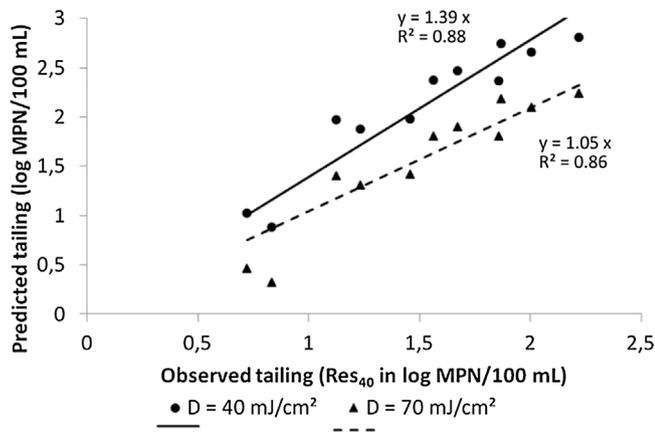


Fig. 8. Correlation between observed tailing for coliforms (measured by Res_{40}) and predicted tailing from Loge et al. model [30]. Two fluences were tested as variables: 40 or 70 mJ/cm^2 .

species in the coliforms group (Fig. 7). Enterococci are mainly in the form of non-mobile cells and aggregated in chains, and thus prone to self-aggregation [29].

The effect of mixed liquor blending with the secondary effluent was not significantly different regarding to the type of microorganism considered (comparable value of the slope of the linear regression in Fig. 7), which tend to confirm that increasing aggregation was mainly due to large particles addition.

Res_{40} determination for activated-sludge effluents of degraded quality accounted for corrected REF using the empirical correlation presented in Fig. 6. A strong linear regression ($R^2 > 0.85$) was established between Res_{40} and turbidity (Fig. 7), UVT_{254} , or TSS. These parameters are representative to an input of suspended particles from mixed liquor. According to Azimi et al. [26], the fraction of microorganisms responsible for tailing is located in the compact cores of the liquor flocs. Larger flocs are more prone to induce tailing since they have several cores.

Our results showed that it may be possible to predict the potential for tailing with a single indicator of suspended particles presence, such as turbidity, TSS or UVT_{254} . These results were obtained from a single WWTP, even if the blending with mixed liquor represented several levels of degraded quality of the secondary effluent. Loge et al. [30] developed an empirical model for coliforms to predict tailing based on the following functional form:

$$N = f(D)^n \quad (3)$$

$$f = A(TSS)^a(UVT_{254})^b \quad (4)$$

where N is the effluent coliform density (MPN/100 mL) after exposure to a given fluence D of UV light and n , A , a and b are empirical coefficients whose value is equal to -1.877 ; $10^{1.133}$; 0.976 and -4.053 respectively [30]. Comparison between the model and Res_{40} values for coliforms is presented in Fig. 8. Two fluences were tested to build the model: 40 and 70 mJ/cm^2 . Even if linear correlations were observed with Res_{40} values in both cases ($R^2 > 0.85$), predicted data were closer to measured values of Res_{40} when $D = 70 mJ/cm^2$ (no significant difference, $p = 0.55$) than when $D = 40 mJ/cm^2$ (significant difference, $p < 0.05$) (Fig. 8). These results may be explained by the fact that Loge et al. used a mathematical simulation (Point Source Summation) to determine the UV fluences applied in their reactor. This method tend to overestimate the applied fluences in comparison with REF determination by biosimetry [30].

Generalization of the correlations presented in this study must be done with caution. As a matter of fact, if the relationship between tailing and suspended solids content has been well-described previously [9,17,18,22], few studies report linear correlations. For instance, Qualls

et al. [18] described a correlation between the number of particles larger than 40 μm in diameter and the fraction of coliforms surviving a fluence of 26 mJ/cm^2 with a R^2 of 0.60 on a dataset gathering several types of secondary effluents. The authors highlighted the influence of the suspended matter structure, which may explain the weakness of their correlations.

More recently, a significant difference was found in tailing potential between secondary effluents from activated sludge or from trickling filter treatment processes [12]. Even if the floc size was considered as decisive to predict tailing propensity, the tailing level measured on trickling filter effluents was 2 log higher than that measured on activated sludge effluents, despite the PSD measurements showed that both effluents had a similar number of flocs greater than 50 μm . According to Azimi et al., the resistance of compact cores to UV disinfection depends on their physical structure and on their chemical composition [13,26,31]. The three main factors identified in order to limit tailing propensity were 1) low floc sphericity (depending of operational conditions), 2) high sludge retention time (to induce natural decrease of microorganism cultivability), and 3) presence of polyphosphate in the flocs (from the enhanced biological phosphorus removal process).

4. Conclusion

The correlations described in this study are valid for the WWTP studied and its direct application to other types of secondary effluents might not be appropriate, even if our results were in accordance with the model developed by Loge et al. [30] from similar WWTP with activated-sludge processes. Our study demonstrates that such correlations can be made at the scale of a WWTP and they can be used by the wastewater reclamation plant operator to predict the effect of secondary effluent quality degradation on the UV disinfection treatment process at two levels:

- 1) to adjust the UV fluence applied in the reactor in order to maintain the REF defined by increasing UV lamps intensity,
- 2) to define an alarm threshold above which the tailing potential compromises the reclaimed water biological quality

The frequency of the measurements is a key point to ensure the reactivity of the treatment chain. That is why the use of on-line sensors to estimate TSS, turbidity and UVT_{254} is recommended [32]. This study focuses on coliforms, *E. coli* and enterococci, which are the main indicators used to assess water quality with the aim of the reclamation. Further research is needed to study the behavior of other pathogenic microorganisms such as viruses or spores in the presence of suspended particles.

Conflicts of interest

None.

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