



## Modeling of secondary treated wastewater disinfection by UV irradiation: Effects of suspended solids content

Mounaouer Brahmi\*, Nouredine Hamed Belhadi, Helmi Hamdi, Abdennaceur Hassen

Water Research and Technology Center, Borj Cédria Science & Technology Park, P.O. Box 273, Soliman 8020, Tunisia.  
E-mail: [brahmounaouer@yahoo.fr](mailto:brahmounaouer@yahoo.fr)

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### Abstract

This work aimed to study UV-resistant strains of *Pseudomonas aeruginosa*, to propose a formulation of the kinetics of secondary treated wastewater disinfection and to underline the influence of suspended solids on the inactivation kinetics of these strains. Some investigations were carried out for the validation of some simulation models, from the simplest, the kinetics model of Chick-Watson reduced to first order, to rather complex models such as multi-kinetic and Collins-Selleck models. Results revealed that the involved processes of UV irradiation were too complex to be approached by a simplified formulation, even in the case of specific strains of microorganisms and the use of nearly constant UV radiation intensity. In fact, the application of Chick-Watson model in its original form is not representative of the kinetics of UV disinfection. Modification, taking into account the speed change during the disinfection process, has not significantly improved results. On the other hand, the application of Collins-Selleck model demonstrates that it was necessary to exceed a least dose of critical radiation to start the process of inactivation. To better explain the process of inactivation, we have assumed that the action of disinfectant on the survival of lonely microorganisms is faster than its action on suspended solids protected or agglomerated to each others. We can assume in this case the existence of two inactivation kinetics during the processes (parallel and independent) of the first-order. For this reason, the application of a new kinetic model by introducing a third factor reflecting the influence of suspended solids in water on disinfection kinetics appeared to be determinant for modeling UV inactivation of *P. aeruginosa* in secondary treated wastewater.

**Key words:** secondary wastewater; disinfection; modeling; UV irradiation; kinetic; suspended solids

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### Introduction

At the present time, ultraviolet (UV) irradiation is considered as one of the best alternative to chemical disinfection of water (especially chlorination) (Meiting et al., 2009). UV radiations interact with nucleic acids and other vital cellular components, such as proteins and lipids (USEPA, 2003b). The knowledge acquired in this field demonstrates that the use of UV for disinfection is a fast, efficient, safe and cost-effective process (Meiting et al., 2009). It has been used for many years in several countries to disinfect the water (USEPA, 2003b). However, microorganisms have evolved repair mechanisms and can reactivate, once their DNA is partially denatured. Visible light and time may have a positive influence on this process known as reactivation. Because of their broad wavelength spectrum, the UV lamps, only low or medium pressure, are capable of destroying cellular components such as proteins and enzymes, and so avoiding this reactivation. This is justified when the water to be treated must fulfill certain conditions to obtain an optimal effect of UV irradiation.

Physicochemical parameters such as water turbidity, hardness, suspended solids, iron, manganese, humic acids are disruptive factors of UV disinfection. Substances in water weaken the transmission rate, and deposits may also tarnish the UV reactor and taints the tubes of quartz protecting the UV lamp (Sellami et al., 2003). The regular change and cleaning of UV quartz sheath lamps provide a good ray permeability thus good distribution. Besides, several parameters can also influence the rate of microbial inactivation such as the UV dose applied, the stability of disinfectant, the contact time, the pH and the temperature of water, and the number and type of microorganisms in water (in terms of resistance) (Hassen et al., 1997). The relationship between these parameters can be evaluated by means of analytical measurements in the laboratory. However, because of the complex dynamics governing this process, only certain parameters such as the UV dose, the contact time and the content of suspended solids in water can be studied at laboratory scale to establish laws monitoring the UV disinfection. To better explain the process of inactivation, some disinfection kinetic models have been proposed in the literature to validate the experimental results, beginning from the simplest model

\* Corresponding author. E-mail: [brahmounaouer@yahoo.fr](mailto:brahmounaouer@yahoo.fr)

of Chick-Watson of first order to models fairly complex as Collins-Selleck and multi-kinetic models. The aim of this study was to evaluate the kinetics of inactivation of certain isolates of *P. aeruginosa* resistant to UV radiation; to determine the influence of UV dose on the kinetics of disinfection and to establish the best combination of contact-time and UV dose, used to achieve a given quality of treated water. Meanwhile, another important target of this work was to study the influence of suspended solids on the kinetics of disinfection and to exploit results for proposing a formulation of the UV disinfection kinetic of secondary treated wastewater.

## 1 Materials and methods

### 1.1 Experiments in a batch laboratory irradiation device

The laboratory UV device was earlier described by Hassen et al. (1997). All bacterial strains were cultivated to mid-log phase at 37°C in 20 mL of nutrient broth. Each culture was centrifuged at 5000 r/min for 15 min (Hassen et al., 2000) and the pellet was washed twice with sterile distilled water. The washed pellet was resuspended in 10 mL sterile distilled water. Test organisms were then seeded separately into 20 mL of sterile wastewater having a UV transmittance of 50%, to give a viable cell count of approximately  $10^5$  to  $10^6$ /mL, the same mean count as in the secondary wastewater. The suspension was then exposed to UV light for periods varying from 2 to 90 sec (10.7 to 183 (mW·sec)/cm<sup>2</sup>). All irradiation experiments were performed at laboratory temperature of (25 ± 5)°C (Hassen et al., 2000). Petri dishes of 90 mm diameter, containing 20 mL of seeded wastewater, were shaken carefully with a mechanical shaker (Edmond Bühler) for at least 15 min to remove all bacterial aggregates. Seeded wastewater served

for counting bacteria, before ( $N_0$ ) and after exposure ( $N$ ) to a definite UV dose. The layer of water crossed with UV rays was 3-mm depth and each experiment was repeated at least four times. Measurements of incident intensity at the liquid surface, at 254 nm, were done with an Ultraviolet device Vibert-Lourmat digital radiometer. Irradiation dose ((mW·sec)/cm<sup>2</sup>) was calculated as the average incident intensity times over exposure time and was regulated by controlling the exposure time.

### 1.2 *Pseudomonas aeruginosa* strains

Disinfection experiments were conducted using the bacterial species *P. aeruginosa* because of the following reasons: *P. aeruginosa* is an ubiquitous strain, commonly detected in surface water, wastewater, hospitals, air and even in soil and plants, *P. aeruginosa* is easily cultivable; it is the cause of confirmed outbreaks, offering high resistance to UV disinfection (Savoern, 1983). Therefore, its kinetics of inactivation by UV irradiation assumed the same fate as for all other less resistant pathogens. A collection of eight strains of *P. aeruginosa* were irradiated with different UV doses and all conditioned by 7 singular contact times ranging between 2 and 30 sec (Table 1).

### 1.3 Effects of bacterial density associated with particulate matter

Bacteria in wastewater are often bonded together as a floc, or associated with particulate matter (suspended solids). These organisms appear more difficult to be disinfected than their free-floating counterparts. Thus, as the dispersed or singlet bacterial organisms are quickly inactive, continued increase of the UV dose will result in less effective responses since the residual active bacteria are being protected in the particulates. The bacterial density associated with particulate matter,  $N_p$ , can be achieved by

**Table 1** Treatment by UV irradiation of references and laboratory strains of *P. aeruginosa*

Strain	2 sec <sup>a</sup>		4 sec		6 sec		8 sec		10 sec	
	$D_2$	$N_2/N_0$	$D_4$	$N_4/N_0$	$D_6$	$N_6/N_0$	$D_8$	$N_8/N_0$	$D_{10}$	$N_{10}/N_0$
S1	10.7	0.0044	21.44	0.0044	32.96	0.001	42.8	0.00023	53.6	0.0003
S2	11.6	0.01	23.2	0.01	34.8	0.0008	46.4	0.00083	56	0.0008
S3	10.36	0.0018	20.72	0.0018	31.08	0.0003	41.4	0.00021	51.8	0.0002
S4	11.28	0.0045	22.56	0.0018	33.84	0.0006	45.12	0.00021	56.4	0.0006
S5	11.72	0.01	23.44	0.0044	35.16	0.0040	46.88	0.0018	58.6	0.0004
S6	12.2	0.01	24.4	0.00037	36.6	0.0018	48.8	0.00022	61	0.0008
S7	12.12	0.01	24.24	0.0018	36.36	0.0045	48.48	0.00057	60.6	0.0018
S8	12.2	0.01	24.36	0.0045	36.6	0.0008	48.72	0.00046	61	0.0004
Strain	12 sec		15 sec		20 sec		30 sec			
	$D_{12}$	$N_{12}/N_0$	$D_{15}$	$N_{15}/N_0$	$D_{20}$	$N_{20}/N_0$	$D_{30}$	$N_{30}/N_0$		
S1	64.03	0.00044	80.4	0.00044	107.2	0.0003	160.8	0.00015		
S2	69.6	0.00083	87	0.00037	116	0.00008	174	0.000006		
S3	62.1	0.00037	77.7	0.00006	103.6	0.00006	155.4	0.00002		
S4	67.68	0.00021	84.6	0.00008	112.8	0.00003	169.2	0.00021		
S5	70.32	0.00037	87.9	0.00037	117.2	0.00008	175.8	0.000064		
S6	73.2	0.00083	91.5	0.00037	122	0.00008	183	0.000064		
S7	72.72	0.00083	90.9	0.00083	121.2	0.00033	181.8	0.00021		
S8	73.08	0.00037	91.5	0.00037	122	0.00037	183	0.00003		

S1: *P. aeruginosa* 15442; S2: *P. aeruginosa* 15442 V1; S3: *P. aeruginosa* 15442 V2; S4: *P. aeruginosa* 15442 V3; S5: *P. aeruginosa* (S21)0; S6: *P. aeruginosa* (S21) variant V1; S7: *P. aeruginosa* (S21) variant V2; S8: *P. aeruginosa* (S21) variant V3. <sup>a</sup> Exposure time;  $D$  (mW·sec)/cm<sup>2</sup>: UV doses;  $N$ : number of bacteria after the period of exposure to laboratory light;  $N/N_0$ : rate of inactivation of microorganisms after exposure to UV;  $N_0$ : number of microorganisms at the instant  $T = 0$  ( $N_0 = 10^8$  organisms/100 mL).

the UV process and is determined as a function of suspended solid (SS) concentration (a regression analysis of the log of the effluent (after exposure) *P. aeruginosa* density as a function of the log of the effluent SS concentration showed the relationship to be linear). The linear regression analysis of the combined data yielded the expression:  $N_p = a \times SS^b$  (Sheible, 1987).

## 2 Results and discussion

### 2.1 Inactivation kinetics of selected strains of *P. aeruginosa* by UV<sub>254</sub>

Disinfection is a gradual process involving a series of steps of physical, chemical and biochemical aspects. The design and management of disinfection systems require knowledge of inactivation kinetics of pathogenic microorganisms (USEPA, 2003a). As mentioned above, the study of inactivation kinetics was carried out using 10 different strains of *P. aeruginosa*.

The inactivation kinetics of these strains showed generally two consecutive phases: a rapid phase and a relatively slower one. Therefore, the importance of the initial phase was considered. In fact, it was an abatement rate higher than 3 logU (log units) after only 4 sec of UV exposure, which led us to conclude that the first moments of UV exposure, corresponding to relatively low irradiation doses (50 to 100 (mW·sec)/cm<sup>2</sup>), was crucial in the disinfection by UV. This result confirms those of reported by Hassen (1998). The review of the inactivation rate of each strain studied (Table 1) showed that for some strains, such as S1, S2, S5, and S6, the efficiency of treatment was improved by increasing UV dose but only to a limited value corresponding to a threshold dose and to a contact time of 8 sec. The limit values of inactivation rate were 3.63, 3.08, 2.74 and 3.67 logU, respectively. The abatement rate did not exceeded for this strain at a value of 3.1 U-log even after an exposure time of 30 sec. For strains S7 and S3, the average abatement fluctuated between 3.41 and 3.82 logU, respectively. Although this resistance variability to UV rays action was well documented in the literature, it has to be especially confirmed at the molecular level.

### 2.2 Modeling the kinetics of disinfection by UV irradiation

The design and management of disinfection systems require knowledge of removal kinetics of pathogenic microorganisms (USEPA, 2003a). It seeks to determine the influence of UV dose on disinfection kinetics. In order to find out the best combination of contact time-UV dose and to predict the outcomes of UV disinfection, we used more or less empirical approaches. These approaches were based on experimental studies using: a laboratory disinfection device, 8 strains of *P. aeruginosa* grown on nutrient agar (property of Pasteur Institute, Tunisia) and simulation models, from the simplest, model of Chick-Watson reduced to first-order kinetics, to quite complex models such as multi-kinetic and Collins-Selleck models. The model of Chick-Watson has been primarily used to

express the kinetics of disinfection with chemical disinfectants (Rhodes et al., 1977; Hart and Vogiatzis, 1982; Roustan et al., 1991). The first-order kinetics is expressed as follows:

$$dN/dt = -K \times C^n \times t \quad (1)$$

The integration of this expression gives:

$$N/N_0 = e^{-KC^n t} \quad (2)$$

where,  $C$  is the concentration of disinfectant in the environment;  $K$  is a coefficient reflecting the specific case of disinfecting fatality potential;  $n$  is a coefficient of dilution, which is a function of disinfectant and pH in the medium (the value of  $n$  is usually close to unity) and  $t$  is the exposure time of microorganisms to disinfectant.

In the case of UV disinfection, an amendment to this model was made by replacing the concentration of chemical disinfectant ( $C$ ) by the intensity of UV radiation as proposed by Haas (1990). The disinfection kinetics could be rewritten as follows:

$$dN/dt = -K \times I^n \times N \quad (3)$$

The integration of this expression gives:

$$N/N_0 = e^{-KI^n t} \quad (4)$$

The change to logarithmic form and using a linear regression, the kinetic parameters ( $K$  and  $n$ ) of the latter expression could be determined as follows:

$$\ln(-\ln(N/N_0)) = \ln K + n \ln I + \ln t \quad (5)$$

When the coefficient  $n$  is less than 1, the disinfection process is more controlled by the contact time than the UV dose. When  $n$  is greater than 1, the UV dose takes precedence over the contact time in the control of the process (Leahy et al., 1987).

In this study, the curve showed usually a significant gap between the experimental points and those simulated by the model in the case of all studied strains of *P. aeruginosa* (results not shown). In the same way, the determination of  $\varepsilon$ , a representative parameter of the difference between the experimental values  $(N/N_0)_{\text{mes}}$  and values calculated by the model  $(N/N_0)_{\text{cal}}$ , appears important for all strains (Table 2). Therefore, we found that the model of Chick-Watson, reduced to a first-order kinetic with  $n = 1$ , showed its limits, and that the inactivation process is most often non-uniform, and does not necessarily comply, as implies a first-order kinetics, with an exponential law (Hassen, 1998; Shayeb et al., 1998). However, the adopted experimental protocol showed a very noticeable reduction rate for low doses of radiation. The minimum dose used was 10.7 (mW·sec)/cm<sup>2</sup> (Table 1). The importance of UV radiation intensity of the lamp allows achieving a yield rate of 2 logU after only two seconds of exposure.

A reduction of three additional logU could not be reached, even after an exposure time of 30 sec. It is therefore necessary to assume the existence of at least two

**Table 2** Kinetics characteristics of all the disinfection models studied during UV irradiation

Strain	Chick-Watson			Amended Chick-Watson				Collins-Selleck			
	$K_1$	$R_1^2$	$\varepsilon_1$	$A$	$K_2$	$R_2^2$	$\varepsilon_2$	$n$	$\tau$	$R_3^2$	$\varepsilon_3$
S1	0.04	-0.27	0.70	0.0558	0.01	0.69	0.06	0.75	0.9	0.69	0.1
S2	0.08	0.58	0.41	0.0028	0.02	0.63	0.067	0.91	1.92	0.80	0.00013
S3	0.09	0.63	1.07	0.002	0.03	0.85	1	0.47	1.77	0.85	0.0040
S4	0.08	0.55	0.39	0.0019	0.02	0.57	0.010	1.1	2.1	0.81	0.0037
S5	0.07	0.54	0.43	0.0036	0.02	0.51	0.01	0.96	1.85	0.64	0.0035
S6	0.05	0.52	1.17	0.0032	0.01	0.56	1	2	2.01	0.82	0.0143
S7	0.06	0.44	0.50	0.0026	0.01	0.52	0.0091	0.1	1.11	0.75	0.0053
S8	0.07	0.51	0.44	0.0027	0.02	0.52	0.0096	0.62	1.55	0.68	0.0019

$A$ ,  $K_1$ ,  $K_2$  and  $K_3$ : characteristics of the models;  $R_1^2$ ,  $R_2^2$  and  $R_3^2$ : coefficients of determination;  $n$ : parameters of adjustment of the model;  $\varepsilon$ : difference between calculated and measured or experimental values =  $\sqrt{\sum [(N/N_0)_{\text{cal}} - (N/N_0)_{\text{exp}}]^2}$ .

stages during the inactivation process of which only the second was explored during the tests. The application of a first order kinetic during the second stage requires the modification of the model by introducing a dimensionless coefficient  $A$ , to reflect the reduction achieved during the first fast kinetics stage (Hart and Votgiatzis, 1982). The expression of bacterial reduction model becomes as follows:

$$N/N_0 = Ae^{-Kt} \quad (6)$$

With  $A$  representing the initial reduction in the number of bacteria. The parameters to identify in this case were,  $K$  and  $A$ .

In the same way, passing to the logarithm scale, the expression becomes:

$$\ln(N/N_0) = \ln A - KI \quad (7)$$

The application of this model to the results presented in Tables 1 and 2, and for all strains studied, leads to a comprehensive expression:

$$N/N_0 = 0.0029e^{-0.0229It} \quad (8)$$

We can determine the kinetic equations and the coefficient of reliability of the model for each strains studied using a linear regression. The kinetic parameters of this modified model ( $A$ ,  $K$ ,  $R^2$  and  $\varepsilon$ ) are grouped in Table 2.

By calculating the difference:

$$\varepsilon = \sqrt{\sum [(N/N_0)_{\text{cal}} - (N/N_0)_{\text{exp}}]^2}$$

for these two models, the values obtained depending on the model of Chick-Watson in its modified form were smaller than those encountered using the same model in its initial form. In the same way, the coefficients of determination  $R^2$  obtained using the amended model of Chick-Watson were generally higher than those obtained using the same model in its original form. Thus, we found that the adjustment of the same model but considering an initial reduction describes quite good the kinetics of disinfection for the most studied strains.

$$\ln(N/N_0) = Ae^{(-K \ln r)} \quad (9)$$

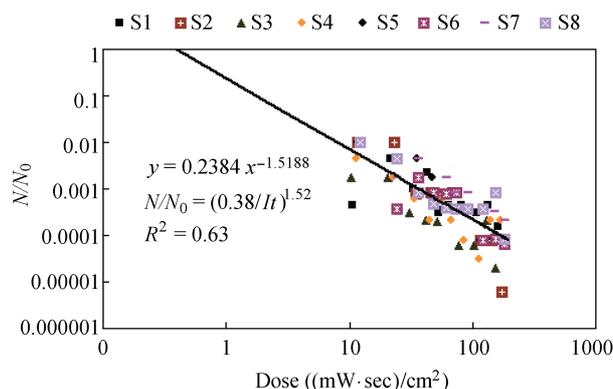
On the other hand, a phenomenon of initial delay (latency of the kinetics) was sometimes found for the majority of bacterial strains used for this experiment. The use of the

proposed model of Collins and Selleck (1972) was justified in this situation (WEF, 1996). As a matter of fact, besides the slowdown in inactivation rate for the high doses of radiation (Shayeb et al., 1998), this model admitted the existence of a period of initial latency. Unlike chemical disinfection, the latency period could be explained here, not by the time required to spread the disinfectant and its incorporation into active sites of microorganisms, but by the fact that the dose of radiation absorbed by microorganisms might reach a critical threshold to become lethal. This model was expressed by the two following relations:

$$N/N_0 = 1 \quad \text{for } It \leq D_m \quad (10)$$

$$N/N_0 = D_m/(It)^n \quad \text{for } It \geq D_m \quad (11)$$

$D_m$  or  $\tau$  is the minimal dose of radiation to be reached to start the process of micro-organism inactivation,  $n$ : a constant. Accordingly, the parameters  $\tau$  and  $n$  could be determined by the transition to the logarithmic form and using a linear fit. Figure 1 shows, for instance, the position of experimental points as compared to the curve of adjustment for the studied strains. We noticed in general that it was necessary to exceed a minimum radiation dose in order to start the critical process of inactivation (Fig. 1). The obtained values seemed valid for all examined strains, below the UV dose of 5.5 (mW·sec)/cm<sup>2</sup> supposed necessary by Wolfe (1990) to achieve 90% of *P. aeruginosa* inactivation. In the same way, the determination of  $\varepsilon$ , a parameter representing the difference between the



**Fig. 1** Kinetics of UV inactivation of selected *P. aeruginosa* approached according to Collins and Selleck model.  $n = 1$ .

measured values  $(N/N_0)_{mes}$  and the calculated ones by the model  $(N/N_0)_{cal}$ , appeared very low for all strains as compared to the values calculated using the model of Chick-Watson in its original form or modified (Table 2). Consequently, Collins and Selleck model was likely to be the most efficient in terms of changing the kinetics during the disinfection process. However, this model did not give an unexpected explanation for the kinetics decrease when the dose increased. The low values of parameter  $\tau$  showed that the disinfection process started quickly with a relatively short latency period.

### 2.3 Impact of suspended solids content on UV disinfection

The turbidity of water makes the UV rays transmission difficult and reduces therefore their effectiveness. Scheible (1987) found that the number of fecal coliform associated to suspended particles was dependent on water solid content. He proposes to subdivide the whole micro-organism load in water into two categories: micro-organisms isolated and therefore vulnerable, and micro-organisms associated with suspended particles and therefore invulnerable. This subdivision of microorganisms in two groups led to the following expression of inactivation kinetics:

$$N' = N_0e^{(-Kt)} + N_p \tag{12}$$

where,  $N_0$  is the number of micro-organisms isolated per unit volume of water ( $N'_0 = N_0 - N_p$ );  $N_p$  is the number of micro-organisms per unit volume of water inaccessible to UV radiation; and  $N'$  is the number of micro-organisms remaining after water treatment with UV radiation  $D$  ( $N' = N - N_p$ ). According to this model, it was accepted that the isolated micro-organisms were inactivated according to first-order kinetics. It was also recognized that a residual number of micro-organisms ( $N_p$ ) persist in water, whatever the radiation dose applied. Under these adopted operating conditions, it was not possible to fall below a level of microorganisms of  $10^3$  per 100 mL for most of the tested strains. During the experimental study, the physico-chemical characteristics of treated wastewater by trickling filter did not greatly changed.

Values fluctuated between 47% and 49% for UV transmission and 15 to 27 mg/L for TSS (total suspended solids) on average. This concentration of suspended particles was unlikely to be the only reason for hindering the process of inactivation at this high level. Other factors related to the operating conditions or to the type of micro-organisms could have been behind this observation. The research work of Scheible (1987) on the installation of Port Richmond in France has led to propose a power function expressed as follow:

$$N_p = aC_{ss}^b \tag{13}$$

where,  $C_{ss}$  is the concentration of suspended solids in water;  $a$ ,  $b$  are two constants. For fecal coliform,  $a$  and  $b$  were 0.26 and 1.96, respectively (Scheible, 1987). In the case of treated wastewater by trickling filter and for all studied strains of *P. aeruginosa*, these constants were 0.36

and 3.67, respectively thus:

$$N_p = 0.36C_{ss}^{3.67} \tag{14}$$

As mentioned above, we assume that the microorganisms were inactivated according to first-order kinetics and that the experimental exploration only concerned the second stage of inactivation process. The number of still viable microorganisms in water having received a  $D$  dose of UV radiation is thus given by:

$$N' = AN'_0e^{-KD} + aC_{ss}^b \tag{15}$$

The product  $AN'_0$  represents the number of microorganisms still viable at the end of the first and fast stage of UV inactivation process. In the case of *P. aeruginosa* and the treated wastewater used, this relationship was:

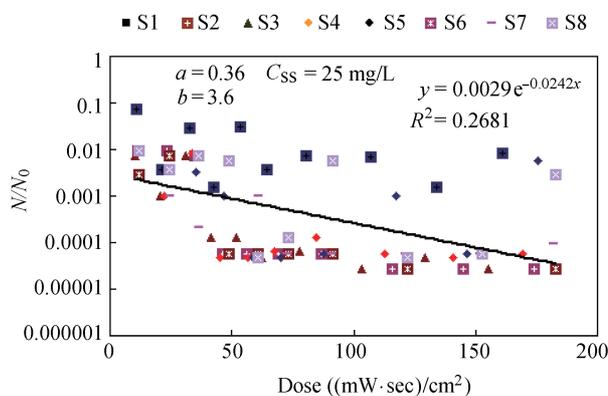
$$N' = 0.0029N'_0e^{-0.0242D} + 0.36C_{ss}^{3.67} \tag{16}$$

This equation could be written as the form below based on the experimental results illustrated in Fig. 2.

$$N' = 0.0029N_0e^{-0.0242D} + 0.36(1 - 0.0029e^{-0.0242D})C_{ss}^{3.67} \tag{17}$$

We have reported on first-order kinetics frequently observed during the inactivation of different types of microorganisms with a certain limit (nearly 2 logU of abatement). Beyond this limit, a slowdown in inactivation rate was often noticed.

This decrease in radiation efficiency, noted when increasing the radiation dose, was often attributed at first to the formation of microorganism aggregates, and secondly to the association of these microorganisms to suspended particles in water. Aggregate-borne microorganisms are protected against the action of UV rays. As previously underlined, Scheible (1987) divided all microorganisms into two types: free or isolated microorganisms, and those associated with suspended solid particles in water. It is assumed that only the first type was available to UV radiation, and therefore vulnerable. By slightly deviating



**Fig. 2** Kinetics of UV inactivation of *P. aeruginosa* according to amended Chick Watson model and taking into consideration the impact of suspended solid content of water.  $a$  and  $b$ : characteristics of the model;  $C_{ss}$ : concentration of suspended solids.

from this hypothesis, we assume that two categories of microbiological population existed in water:

Microorganisms which, for one reason or another, were readily exposed to radiation. The rate of inactivation of these microorganisms is rapid.

Microorganisms less accessible to radiation therefore inactivated according to a slower kinetic. By assuming that these two concomitant mechanisms of the first order were independent, we can express the rate of inactivation of the total number of microorganisms by applying multi kinetics model of first order, expressed by the relationship as follows:

$$N_0 = Pe^{-K_1D} + (1 - P)e^{-K_2D} \tag{18}$$

where,  $P$  is fraction of microorganisms which is more susceptible to UV radiation;  $D$  is UV dose in (mW·sec)/cm<sup>2</sup>;  $K_1$  and  $K_2$  are kinetic constants for each category of microorganisms.

In this study, the applicability of this model was tested to characterize the inactivation of *P. aeruginosa* in treated wastewater by determining the values of the constants  $P$ ,  $K_1$  and  $K_2$  (Fig. 3). We were able to express the turnover rate by the following equation:

$$N/N_0 = 0.9917e^{-0.39D} + 0.0031e^{-0.89D} \tag{19}$$

This model assumed that it was still possible to achieve the complete inactivation of all microorganisms if we applied enough UV dose. We observed, however, that

during UV disinfection experiments, it was practically not possible to go down below a certain level of abatement. Shayeb (2000) attributed this fact to the high concentration of suspended solids in water. To integrate this concept, we assumed that the fraction of vulnerable microbiological population in water does not exhibit the same sensitivity to UV radiation. In the case of homogeneous populations, the non-uniformity of radiation throughout the reactor's area (irradiation room) or the heterogeneity of the environment might explain the non-uniformity of radiation efficacy. The position of an organism with respect to radiation source and the nature of the environment penetrated by rays have a strong influence on the kinetics of inactivation. Taking into consideration the experimental results presented in Tables 1 and 2, three main stages could be distinguished as follows:

A first stage during which the density of microorganisms is important, therefore, radiation efficiency is the greatest. During this stage, the most vulnerable microorganisms are inactivated.

A second stage concerning lonely organisms but less accessible to the radiation, hence showing a slower rate of inactivation.

A third stage related to organisms which are inaccessible to radiation because they are associated to suspended solid particles. During this period, the number of viable microorganisms remains stable. This result corresponds to a null inactivation kinetic. Taking into consideration this approach, the number of micro-organisms remaining viable in water and irradiated with a  $D$  dose was given by the following expression:

$$N' = N'_0(Pe^{-K_1D} + (1 - P)e^{-K_2D}) + N_p \tag{20}$$

The characteristic kinetic parameters of *P. aeruginosa* inactivation in secondary treated wastewater used in this study were 0.9928 for  $P$ , 0.39 for  $K_1$  and 0.031 for  $K_2$ , respectively; for this reason, the expression became:

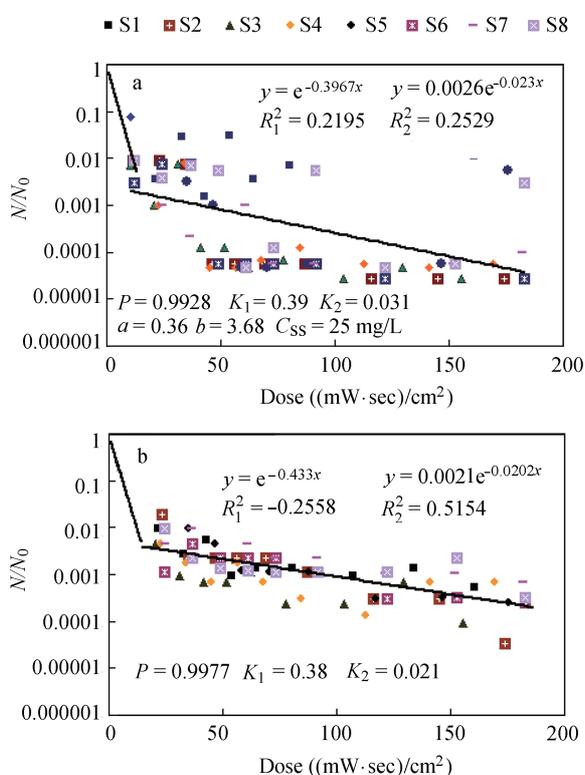
$$N' = (N_0 - 0.26C_{ss}^{3.8})(0.9928e^{-0.39D} + 0.0021e^{0.031D}) + 0.26C_{ss}^{3.8} \tag{21}$$

An illustration of this model is shown in Fig. 3.

### 3 Conclusions

This kinetic study showed that the resistance of *P. aeruginosa* to UV radiation varied from one strain to another. Some strains showed a significant decrease when increasing the UV dose in contrast to other strains with abatement rates still low.

The modeling study of UV disinfection kinetics for all studied strains showed that the law of disinfection proposed by the model of Chick-Watson poorly simulated the experimental data. A divergence occurred on the rate of inactivation that was not quite linear. Thus, the original form of this model is not representative of disinfection kinetics. Modification taking into account the change of disinfection rate during the process did not significantly improved results, indeed. The application of a first order



**Fig. 3** Kinetics of UV inactivation of selected *P. aeruginosa* approached according to a multi-action of first order with (a) and without suspended solid content (b).  $C_{ss}$ : concentration of suspended solids;  $a$ ,  $b$ ,  $P$ ,  $K_1$  and  $K_2$ : kinetic characteristics of the model;  $R_1^2$  and  $R_2^2$ : coefficients of determination;  $n = 1$ .

law to the kinetics model of disinfection was therefore possible, if we assumed the existence of two successive steps of different kinetics. Only the second stage was explored during these experiments. The first stage of fast kinetics could only be studied when considering an initial abatement. In the case of the second stage of this model, the presence of suspended particles in water had an important effect on dissipating the radiation energy and therefore on protecting the microorganisms against UV rays. As a conclusion, suspended particles affected directly the effectiveness of the UV disinfection.

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