Advances in Chemical Engineering and Science, 2026, 16(2), 9-24
https://www.scirp.org/journal/aces
ISSN Online: 2160-0406
ISSN Print: 2160-0392

UV-C Photodegradation Kinetics and Fluorescence Dynamics of Fluoroquinolones in the Waters of the Senegal River

Abdourahmane Khonté[1,2*], Coura Dione[1], Abdou Dieng[1], Pape Abdoulaye Diaw[1], Jean Pierre Bakhoum[3], Diégane Sarr[1], Diène Diégane Thiaré[3], Ndeye Arame Diop[1], Atanasse Coly[3], Philippe Giamarchi[2]

[1]Laboratoire Matériaux, Electrochimie et Photochimie Analytique, Université Alioune Diop, Bambey, Sénégal
[2]Laboratoire OPTIMAG, Université de Brest (UBO), Brest Cedex, France
[3]Laboratoire de Photochimie et d'Analyse (LPA), Faculté des Sciences et Techniques, Université Cheikh Anta Diop, Dakar, Sénégal
Email: *abdourahmane.khonte@uadb.edu.sn

How to cite this paper: Khonté, A., Dione, C., Dieng, A., Diaw, P.A., Bakhoum, J.P., Sarr, D., Thiaré, D.D., Diop, N.A., Coly, A. and Giamarchi, P. (2026) UV-C Photodegradation Kinetics and Fluorescence Dynamics of Fluoroquinolones in the Waters of the Senegal River. *Advances in Chemical Engineering and Science*, **16**, 9-24.
https://doi.org/10.4236/aces.2026.162002

Received: November 27, 2025
Accepted: April 27, 2026
Published: April 30, 2026

Abstract

This study investigates the UV-C photodegradation kinetics of ofloxacin (OFX) and norfloxacin (NFX) in relation to their fluorescence lifetimes and pH-dependent speciation. While NFX consistently follows first-order kinetics under all conditions, OFX exhibits zero-order kinetics at pH 4 and 10, attributed to saturation of photon absorption sites. OFX degrades fastest under basic conditions, whereas NFX is more stable in acidic media and degrades more rapidly near neutral pH. Fluorescence lifetimes measured at pH 4 show that OFX (τ_F = 7.08 ns) is intrinsically more photostable than NFX (τ_F = 2.04 ns), although in river water, environmental factors such as dissolved organic matter and reactive oxygen species accelerate OFX degradation. Zwitterionic forms of both antibiotics display enhanced photoreactivity due to a favorable electronic structure and higher UV absorbance. Although UV-C irradiation was used, these controlled experiments provide mechanistic insights relevant to the environmental fate of fluoroquinolones.

Keywords

Fluoroquinolones, Photodegradation, Photolysis Kinetics, Fluorescence Lifetime, Ofloxacin, Norfloxacin, pH, UV-C Irradiation

1. Introduction

Fluoroquinolones (FQs) represent a class of synthetic broad-spectrum antibiotics widely used in both human and veterinary medicine for the treatment of numerous bacterial infections [1]. Among the most common are norfloxacin (NFX) and ofloxacin (OFX), known for their therapeutic efficiency, chemical stability, and high bioavailability [2]. These compounds act mainly by inhibiting the enzymes DNA gyrase and topoisomerase IV, which are essential for bacterial replication [3]. However, the extensive and continuous use of these molecules, combined with their low biodegradability, has led to their increasing accumulation in aquatic environments. A substantial proportion (up to 70%) of administered fluoroquinolones is excreted unchanged or only slightly metabolized and subsequently released into domestic, hospital, or industrial wastewater. These substances are frequently detected in wastewater effluents, surface waters, and sometimes even groundwater, where they are considered emerging pollutants [4]. Their persistence and bioaccumulation pose significant ecotoxicological risks, notably the development of bacterial resistance and the disruption of aquatic ecosystems [5]. Once introduced into natural environments, the fate of fluoroquinolones depends on several processes, including adsorption, hydrolysis, microbial biodegradation, and photolysis. Among these mechanisms, photodegradation plays a central role, particularly in surface waters exposed to sunlight [6]. Photolysis involves the absorption of ultraviolet radiation by the molecule, leading to electronic excitation followed by the cleavage or transformation of key chemical bonds. Fluoroquinolones contain chromophoric groups such as aromatic rings and conjugated carbonyl functions, which give them strong absorption in the UV region ($\lambda = 200$ - 350 nm) [7]. This property makes these compounds highly susceptible to photochemical processes capable of generating photodegradation products (PPDs), whose toxicity or antibacterial activity may be altered, sometimes increased or decreased [8]. The pH of the medium, the presence of metal ions (Fe^{3+}, Pb^{2+}, Cu^{2+}), dissolved organic matter (DOM), and other photoactive substances can influence both the kinetics and pathways of photodegradation [9]. For example, humic acids may absorb part of the UV radiation and act either as filters or as photosensitizers depending on the aqueous matrix. Natural photolysis is mainly driven by solar UV-A and UV-B radiation; however, under experimental conditions, the use of UV-C lamps (200 - 280 nm) allows the study and acceleration of degradation processes under controlled conditions. UV-C radiation, particularly at 254 nm, exhibits high photon energy (4.88 eV) capable of directly breaking C-N, C-F, or C=O bonds present in fluoroquinolones [10]. Laboratory studies of this kind simulate the photochemical behaviour of these molecules under natural conditions while allowing detailed kinetic analysis. The application of controlled photodegradation methods is essential not only for understanding the photochemical stability of fluoroquinolones but also for designing advanced water treatment processes (AOPs) combining irradiation with oxidants such as H_2O_2, TiO_2, or O_3 [11] [12].

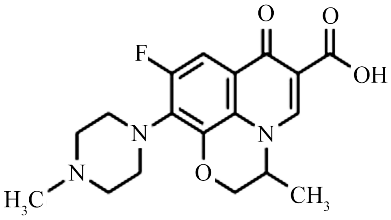
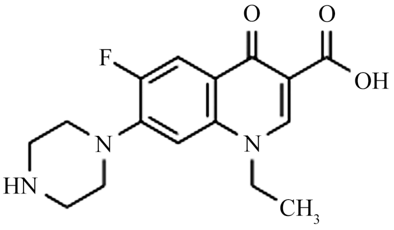
This work aims to deepen the understanding of the photochemical behaviour of ofloxacin (OFX) and norfloxacin (NFX) in Senegal River water under UV-C irradiation, with a particular focus on the relationship between their photodegradation kinetics and fluorescence lifetime. The study examines the photolysis of both fluoroquinolones at different pH values, determining key kinetic parameters (rate constant, half-life, correlation coefficient r^2) and identifying the reactive ionic species involved. A comparative approach between OFX and NFX enables the link between their structural differences, photostability, and excited-state dynamics to be established, while comparison with recent literature places the results within the context of current research. Finally, the environmental implications of these photochemical processes are discussed in relation to the monitoring and management of waters contaminated by antibiotics, providing predictive insights into their persistence in aquatic ecosystems.

2. Materials and Methods

2.1. Reagents

Stock solutions of ofloxacin (OFX) and norfloxacin (NFX), at a concentration of **300 mg·L^{-1}**, were prepared from high-purity standards (≥98%, Sigma Aldrich). The pH of the experimental solutions was adjusted using **sodium hydroxide pellets** (**NaOH**, **97%**) and **hydrochloric acid** (**HCl**, **37%**), also supplied by Sigma Aldrich (Taufkirchen, Germany). All solutions and dilutions were prepared with **ultrapure water** produced using a Milli-Q purification system. The main physicochemical properties of ofloxacin and norfloxacin are summarized in Table 1.

Table 1. Chemical properties of ofloxacin and norfloxacin.

Antibiotics	Chemical Properties		Formula
Ofloxacin	Formula	$C_{18}H_{20}FN_3O_4$	
	Molecular	361.4 g·mol^{-1}	
	Water solubility (25˚C)	28.3 g·L^{-1}	
	Melting point	270˚C - 275˚C	
	pKa (1 - 2)	5.97 - 7.65	
	Log Kow (25˚C)	−0.39	
	Koc	44,100 L·Kg^{-1}	
Norfloxacin	Formula	$C_{16}H_{18}FN_3O_3$	
	Molecular	319.3 g·mol^{-1}	
	Water solubility (25˚C)	178 g·L^{-1}	
	Melting point	227˚C - 228˚C	
	pKa (1 - 2)	6.26 - 8.85	
	Log Kow (25˚C)	−1.03	
	Koc	18.68 L·Kg^{-1}	

Log Kow: octanol-water partition coefficient, **Koc**: organic carbon-water partition coefficient.

2.2. Materials

A 3.5 mL quartz rectangular cuvette was used for sample analysis with a Cary Eclipse VARIAN spectrofluorimeter connected to a microcomputer equipped with the Cary Scan software. The system covers a wavelength range from 200 to 900 nm, allowing the recording of excitation and emission spectra. Buffer solutions were prepared using a Consort C60010R pH meter (Belgium).

The reagents were weighed using a precision balance with an accuracy of 10^{-3} g. For UV-C irradiation, three 15 W germicidal lamps producing UV-C radiation were mounted in a triangular configuration inside the chamber. A Teflon coil was added to the system, allowing sufficient UV-C transmission to generate photoproducts more efficiently in flow conditions compared to the use of standard tubes.

2.3. Preparation of Water Samples

Natural water samples were collected from the Senegal River in the Saint-Louis region using 1.5 L glass bottles according to standard procedures. The samples were filtered through a 25 mm PTFE syringe filter with a 0.2 µm pore size (Sigma-Aldrich) to remove suspended particulates.

Photodegradation experiments were conducted using **untreated river water**, leaving dissolved organic matter (DOM) intact to preserve natural conditions and account for its potential role in photosensitization.

Analytical preconcentration for fluorescence measurements was performed separately using solid-phase extraction (SPE) with reverse-phase C18 cartridges. The cartridges were conditioned with 3 mL of methanol followed by 3 mL of ultrapure water. Then, 50 mL of the natural water samples were passed through the cartridges to concentrate the analytes and reduce residual organic contamination prior to fluorescence analysis.

This approach ensures that **photodegradation kinetics reflect natural water composition**, while **fluorescence measurements are optimized for sensitivity and accuracy**.

3. Results and Discussion

3.1. Spectral and Lifetime Properties

The fluorescence excitation spectra of both antibiotics in water exhibit **three distinct excitation bands** (Figure 1). Both molecules share the first and third excitation bands, appearing at **230 nm** and **326 nm**, respectively. However, the second, most intense excitation band occurs at **287 nm for OFX** and **271 nm for NFX**. The emission spectra show a **single emission band** at **461 nm for OFX** and **415 nm for NFX** (Figure 1).

Lifetimes of the two antibiotics were measured in water at a pH of 4. The emission wavelength of 461 nm was used to measure the lifetime of OFX at a concentration of 0.72 $\mu g \cdot mL^{-1}$, and the lifetime of NFX was measured at 415 nm at a concentration of 0.8 $\mu g \cdot mL^{-1}$. Fluorescence lifetime (τ_F) measurements (Figure 2) give very different results. OFX has a long fluorescence lifetime of 7.08 ns, while NFX has a short one of 2.04 ns only, indicating that τ_F (OFX) = 3.5 τ_F (NFX). The observed difference can be ascribed to the increased molecular rigidity imparted by the oxazine ring in ofloxacin, which bridges the N-1 and C-8 positions. This fused ring system constrains internal degrees of freedom and suppresses non-radiative deactivation pathways such as vibrational and torsional motions, thereby enhancing photophysical stability. In contrast, norfloxacin, which lacks this structural feature, exhibits greater conformational flexibility and a more dynamically accessible π-electron system. As a result, norfloxacin readily populates a triplet excited state with a lifetime on the order of ~1 μs, a process associated with photosensitization and subsequent photodegradation. Ofloxacin, on the other hand, displays a markedly low photodecomposition quantum yield ($\varphi \approx 0.001$), indicative of a highly inefficient intersystem crossing from the singlet to the triplet manifold [13].

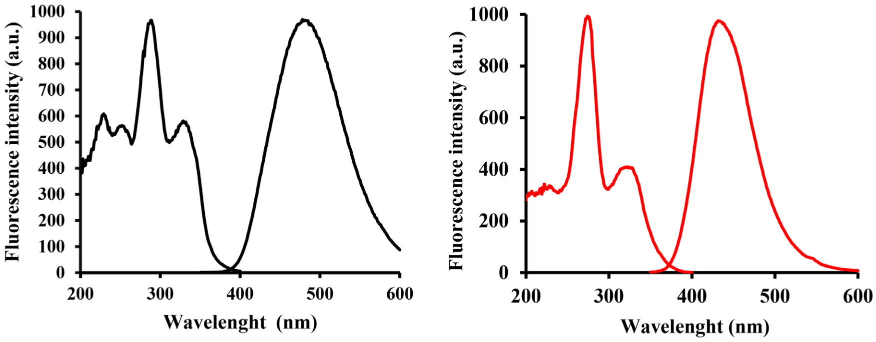


Figure 1. Excitation and emission spectra of OFX (—) and NFX (red curve) at a concentration of 2.5 μg·mL^{-1} in water river by FLUO method.

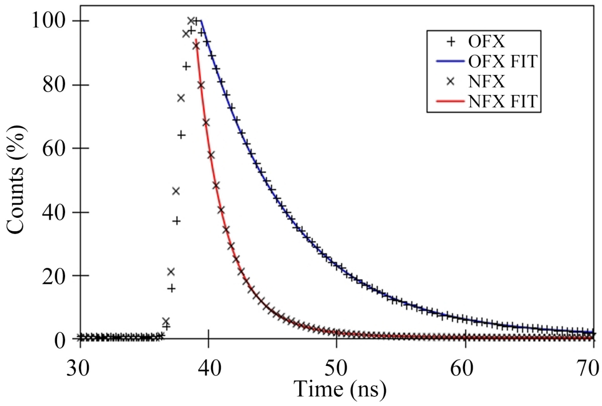


Figure 2. Lifetime measurements measured at a concentration of 2.5 μg·mL^{-1} in water pH = 4: OFX (+ experimental value; — fit) and NFX (x experimental value; red curve: fit).

3.2. Effect of pH

Recent studies have shown that the fluorescence signal of organic compounds is highly sensitive to the pH of the surrounding medium [14] [15]. Therefore, after preparing a solution containing OFX or NFX, a precise amount of acid or base was added to reach the desired pH using a pH meter. The resulting data were plotted (Figure 3) to generate a curve representing fluorescence intensity as a function of pH. For OFX, fluorescence intensity **increases with pH**, reaching a maximum at **pH 4**, then gradually decreases up to **pH 10**, and remains constant between **pH 10 and 13**. In contrast, the fluorescence signal of NFX **rises between pH 1 and 2**, then remains nearly constant between **pH 2 and 5**, with a slightly higher signal at **pH 4**. Once the pH exceeds 5, the fluorescence signal progressively decreases until it becomes undetectable.

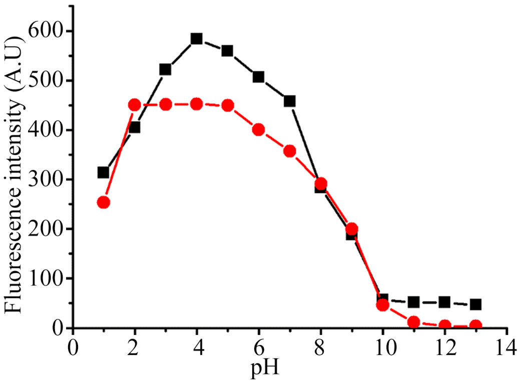


Figure 3. Evolution of the fluorescence intensity of OFX (▪) and NFX (● (red)). Antibiotic concentration (2.5 μg·mL^{-1}).

3.3. Photodegradation Study of Ofloxacin (OFX) and Norfloxacin (NFX)

A comparative study of the photolysis of ofloxacin (OFX) and norfloxacin (NFX) was conducted to evaluate the influence of pH and the aqueous medium on the degradation of these fluoroquinolones under UV-C irradiation. Dilute solutions of both compounds were prepared and placed in UV-transparent quartz cuvettes at a fixed distance from the light source to ensure uniform exposure. Experimental conditions were maintained constant, with an ambient temperature of 25˚C and irradiation times adapted for each molecule. Degradation was monitored by spectrofluorimetry at their respective emission maxima: **λ_{em} = 461 nm for OFX** and **λ_{em} = 415 nm for NFX** (Figure 4(a) and Figure 4(b)). The percentage of photodegradation was calculated using the following equation: $\frac{I_0 - I}{I} \times 100$, where I_0 is the initial fluorescence intensity and I is the intensity measured after **15 minutes for OFX** and **30 minutes for NFX**. During irradiation, the fluorescence intensity of both molecules **decreases gradually**, indicating their transformation into photoproducts. After 15 minutes for OFX and 30 minutes for NFX, the observed photodegradation percentages were: **OFX**: 98% in river water, 41% at pH 4, 84% at pH 7, and 84% at pH 10; **NFX**: 94% in river water, 49% at pH 4, and 73% at pH 7. Photodegradation was particularly pronounced in natural river water, where **dissolved organic matter** (DOM) **and metal ions act as photosensitizers**, **generating reactive oxygen species** (ROS) **such as hydroxyl radicals**,

singlet oxygen, **and organic radicals**, **which accelerate photolysis**. Under acidic conditions, molecules are predominantly **protonated**, reducing UV absorption and reactivity, which explains the low degradation percentages [16]. At neutral pH, fluoroquinolones exist mainly in **zwitterionic forms**, which favor high quantum yields and optimal UV absorption, thereby enhancing photolysis [17]. In basic media, OFX remains highly degraded (84%), suggesting that additional factors, such as radical formation at high pH, contribute to sustained photoreactivity [18]. These observations indicate that the photodegradation of fluoroquinolones strongly depends on **molecular speciation** and the **composition of the medium**. Zwitterionic forms are the most reactive, whereas cationic and anionic forms exhibit relative stability. Photolysis is particularly efficient in natural water, confirming the role of organic photosensitizers in accelerating the photochemical degradation of OFX and NFX [14].

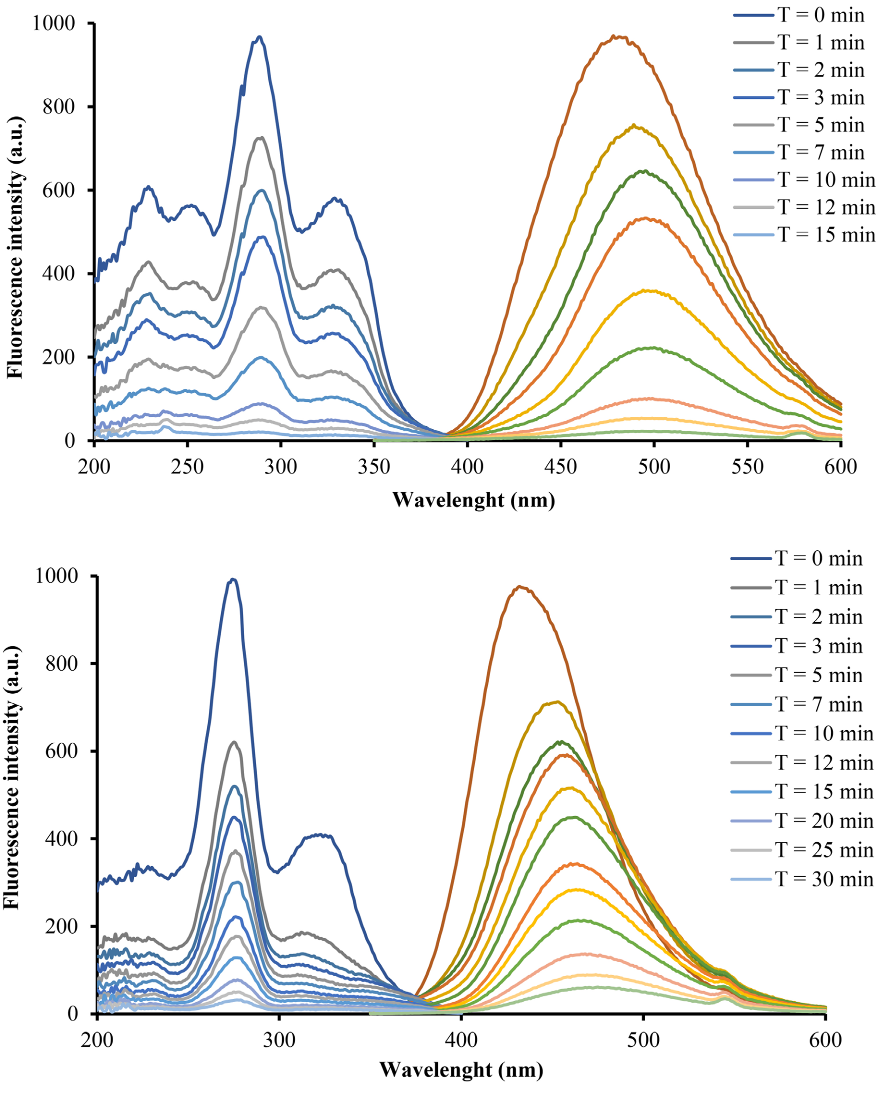
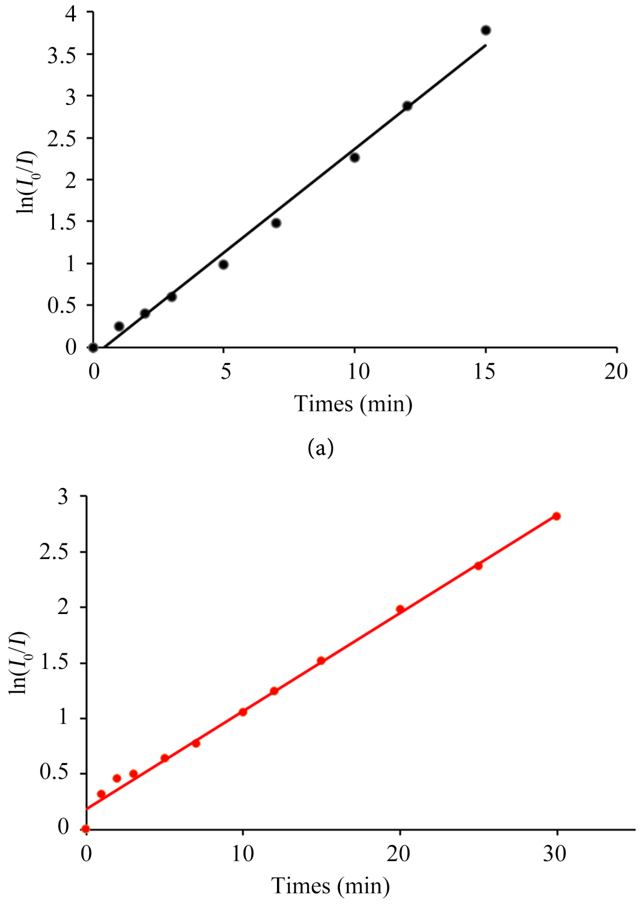


Figure 4. Evolution of the excitation and emission spectra of OFX and NFX in Senegal River water.

3.4. Photodegradation Kinetics of Ofloxacin (OFX) and Norfloxacin (NFX)

The analysis of the fluorescence intensity evolution curves as a function of irradiation time (**Figure 5(a)** and **Figure 5(b)**) allowed the determination of apparent rate constants and the assessment of pH effects on the photolytic stability of ofloxacin and norfloxacin. The photodegradation kinetic parameters of OFX and NFX in pure water and at different pH values are presented in **Table 2**.



(a)

(b)

Figure 5. Photodegradation kinetics of OFX (36.14 ng·mL^{-1}) and NFX (31.94 ng·mL^{-1}) in river water.

Table 2. Photodegradation kinetic parameters of OFX and NFX in river water and at different pH values.

OFX						
Aqueous medium	**Order**^{a}	**(r^2)**^{b}	**$t_{1/2}$ (min)**^{c}	**K**^{d}	**σ (µS/cm)**^{e}	**PPd (%)**^{f}
River water	1	0.992	3	(2.47 ± 0.2) × 10^{-1} min^{-1}	380	98
River water pH 4	0	0.955	35	(1.43 ± 0.1) × 10^{-7} mol·min^{-1}·L^{-1}	950	41
River water pH 7	1	0.992	6	(1.16 ± 0.2) × 10^{-1} min^{-1}	400	84
River water pH 10	0	0.988	2.2	(2.27 ± 0.1) × 10^{-6} mol·min^{-1}·L^{-1}	750	84

Continued

NFX						
Aqueous medium	**Order**[a]	**(r^2)**[b]	**$t_{1/2}$ (min)**[c]	**K (min^{-1})**[d]	**σ (mS/cm)**[e]	**PPd (%)**[f]
River water	1	0.994	8	$(8.8 \pm 0.2) \times 10^{-2}$	420	94
River water pH 4	1	0.990	15	$(4 .5 \pm 0.3) \times 10^{-2}$	1100	49
River water pH 7	1	0.994	8	$(8.7 \pm 0.1) \times 10^{-2}$	580	73

[a] Order = reaction kinetic order. [b] r^2 = kinetic equation correlation coefficient. [c] $t_{1/2}$ = photodegradation reaction half-life time (min). [d] k = photodegradation rate constant (min^{-1}) and absolute error (±). [e] Conductivity of the water samples. [f] Photodegradation percentage.

The photodegradation kinetics of ofloxacin (OFX) were studied in river water and in buffered media at different pH values under UV-C irradiation. The kinetic parameters obtained (Table 2) show a significant variation in the degradation rate and photochemical behaviour of OFX depending on the pH of the medium. In river water and at neutral pH (pH = 7), degradation follows **first-order kinetics** ($r^2 \approx 0.99$), indicating that the photodegradation rate depends directly on the antibiotic concentration. This behaviour is consistent with previous reports [19], which showed that fluoroquinolones undergo first-order degradation under UV irradiation, reflecting a photoinduced process governed by direct absorption of radiation. In contrast, at acidic (pH = 4) and basic (pH = 10) conditions, the reaction follows **zero-order kinetics**, suggesting that the rate becomes independent of concentration. A similar behavior has been reported for several fluoroquinolones under irradiation, particularly when the absorbance of the photoactive species reaches a saturation threshold that renders the reaction rate independent of the initial concentration. In such cases, zero-order kinetics typically arise from the saturation of specific chromophoric groups that absorb UV photons, from light-screening effects occurring under strongly acidic or basic conditions, or from the formation of protonated or deprotonated species that exhibit strong and constant absorbance in the irradiation range (Figure 6) [20]. In the present study, this mechanism provides a consistent explanation for the zero-order behavior observed for OFX at pH 4 and pH 10. At these pH values, OFX exists predominantly in its protonated form (pH 4) or deprotonated form (pH 10), both showing enhanced molar absorptivity in the UV-C region. The resulting saturation of photon absorption leads to constant photolysis rates during irradiation, thereby producing the observed zero-order kinetics.

The **rate constant** (**k**) and **half-life** (**$t_{1/2}$**) confirm the pronounced effect of pH on molecular stability. In pure water ($k = 0.247\ min^{-1}$, $t_{1/2} = 3$ min) and at neutral pH ($k = 0.116\ min^{-1}$, $t_{1/2} = 6$ min), degradation is relatively fast, indicating efficient UV-C absorption. Under acidic conditions, the reaction is significantly slowed ($k = 1.43 \times 10^{-7}\ mol \cdot min^{-1} \cdot L^{-1}$, $t_{1/2} = 35$ min), reflecting greater chemical stability of protonated OFX. At low pH, protonation of the piperazinyl group decreases electron density on the aromatic ring, reducing photon absorption [21]. Conversely, under basic conditions (pH = 10), degradation is markedly accelerated ($t_{1/2}$ = 2.2

min), reflecting increased photo-instability. Deprotonation of carboxylic and ketonic groups favors the formation of photoexcited reactive species (•OH, $O_2•^-$) capable of breaking C-N and C-F bonds within the molecule. This observation aligns with previous studies reporting rapid degradation of fluoroquinolones under alkaline conditions (**Figure 6**) [22]. High correlation values ($0.95 \le r^2 \le 0.99$) confirm the validity of the kinetic models applied and the reliability of the experimental data. Overall, the photolysis of OFX is strongly **pH-dependent**: the molecule is more stable in acidic media and more labile in basic media. These results highlight the importance of environmental pH in the photochemical fate of fluoroquinolones, a key parameter for evaluating their persistence and ecological impact in aquatic environments [23].

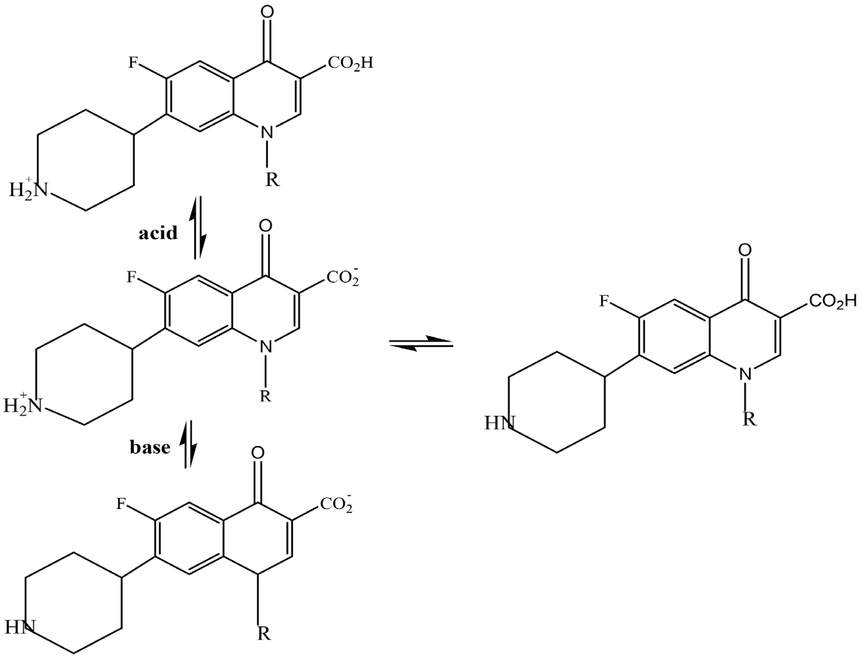


Figure 6. Protonation and deprotonation of fluoroquinolones.

The results show that the photodegradation of NFX follows **first-order kinetics** ($r^2 \ge 0.992$) under all experimental conditions, which is consistent with observations for other fluoroquinolones such as ciprofloxacin and ofloxacin [24]. This kinetics indicates that the degradation rate depends directly on the concentration of NOR in the reaction medium. The lowest rate constant ($k = 0.045\ \text{min}^{-1}$) and the longest half-life ($t_{1/2} = 15$ min) were observed at pH = 4, indicating greater stability of NFX under acidic conditions. This stabilization can be attributed to the protonation of basic functional groups, particularly those in the piperazinyl ring, which reduces the likelihood of forming reactive excited states and thus slows photodegradation [25]. Conversely, under neutral conditions (pH = 7) and in unbuffered water, NOR exhibits similar rate constants ($k \approx 0.087 - 0.088\ \text{min}^{-1}$) and half-lives of 8 minutes. These values indicate that NFX degrades more rapidly at this pH, likely due to the presence of zwitterionic or partially deprotonated forms that favors UV photon absorption and formation of photoactive species [26]. This pH-dependent behaviour has also been reported for other fluoroquinolones, such as levofloxacin and ciprofloxacin, whose photodegradation rates increase as pH approaches neutrality [17]. This suggests that the **ionic form of the molecule** plays a key role in photochemical reactivity, influencing electron distribution and UV absorption efficiency [27]. These observations are consistent with the fact that fluoroquinolones exhibit their highest photoreactivity in the zwitterionic state. This protonation form combines opposite charges within the same molecule, generating strong internal electric fields that favor intramolecular charge-transfer transitions, generally more prone to photodegradation. The zwitterion also displays a higher dipole moment and a more planar conformation of the quinolone chromophore compared with the fully cationic or anionic species, both of which tend to experience electrostatic distortions. Such structural and electronic features enhance the efficiency of photon absorption and increase access to reactive excited states, thereby promoting the formation of photolytic intermediates. This provides a coherent physicochemical explanation for the enhanced photoreactivity observed near neutral pH, where the zwitterionic form predominates. These results show that NFX is more persistent in acidic media (pH < 7) and less stable in neutral waters, which are typical of surface waters. Thus, in the environment, its fate will strongly depend on local pH: faster degradation is expected in neutral to slightly basic waters, while greater accumulation could occur in more acidic environments [28]. Understanding this behavior is essential to predict the persistence and ecotoxicological potential of NFX in aquatic environments exposed to sunlight. Further studies, including the identification of photoproducts and the role of reactive oxygen species, would help clarify the underlying reaction mechanisms.

Although this study employed UV-C irradiation, which possesses higher photon energy than environmentally relevant solar UV-A and UV-B radiation, the results provide valuable insights into the relative photostability and pH-dependent photodegradation mechanisms of fluoroquinolones. UV-C irradiation allows for controlled and accelerated experiments that enhance the detection of subtle kinetic differences between ofloxacin (OFX) and norfloxacin (NFX) and facilitates mechanistic understanding of the roles of zwitterionic, cationic, and anionic species. While the absolute degradation rates under natural sunlight may be slower, the trends observed under UV-C including the influence of pH, the contribution of dissolved organic matter, and the relative susceptibility of different molecular forms remain informative for predicting environmental fate and designing water treatment strategies.

3.5. Comparative Study

The results obtained for the photolysis of **ofloxacin** (**OFX**) and **norfloxacin** (**NFX**) in Senegal River water at different pH values show overall **first-order kinetics**, with apparent rate constants ranging from 0.045 to 0.247 min^{-1} (**Table 2**).

Half-lives vary from 2 to 35 minutes depending on the pH and the compound, confirming rapid photodegradation under UV-C irradiation. These values are consistent with trends reported in recent literature for fluoroquinolones exposed to UV-C or UV-A radiation [29]. Under neutral or basic conditions, OFX exhibits significantly faster degradation (**$t_{1/2}$ ≈ 3 min in pure water**; **2.2 min at pH 10**) than NFX (**$t_{1/2}$ ≈ 8 min in pure water**; **15 min at pH 4**). This difference can be attributed to the chemical structure of OFX, whose piperazinyl group and carboxylic function promote stronger absorption at 254 nm and higher reactivity of anionic forms [30]. These observations are in agreement Wammer *et al.* [29] and Liu *et al.* [31], who showed that OFX photoreactivity strongly depends on its ionic form and the pH of the medium. The rate constant obtained in this study for OFX in pure water ($k = 0.247\ \text{min}^{-1}$) is higher than those reported in previous studies. For example, Sebastian Snowberger *et al.* reported slower photolysis kinetics of fluoroquinolones under UV-C irradiation [32], while studies on ciprofloxacin degradation under UV-based processes also indicate lower apparent rate constants depending on experimental conditions [33]. These variations are likely due to differences in irradiation wavelength, photon flux, and solution composition, which are known to strongly influence photodegradation kinetics. This acceleration can be explained by the higher light intensity and the absence of interfering compounds in the experimental medium used. For NFX, the measured value in our study (**$k = 0.088\ \text{min}^{-1}$**; **$t_{1/2} = 8$ min**) is of the same order of magnitude as that reported by Iqbal *et al.* [34], who found **$k = 0.042\ \text{min}^{-1}$** (**$t_{1/2} = 16.4$ min**) under UV alone. Differences may be attributed to lamp power, initial concentration, and water composition. Other recent studies, including Bobu *et al.* [35] and Cuarda-Correa *et al.* [36], also confirm that NFX exhibits slightly higher photostability than OFX, except in the presence of catalysts or oxidants such as H_2O_2. Zhan *et al.* [37] reviewed the effects of pH, ionic speciation, and experimental parameters on fluoroquinolone photolysis: the neutral or anionic form is the most reactive, whereas the cationic form (dominant at pH < 6) exhibits higher photostability. This trend is fully confirmed by our experimental results, where OFX degradation drastically decreases under acidic conditions (**$t_{1/2}$ = 35 min at pH 4**). Recent work by Niu and Busetti [38] and Zhang *et al.* [39] highlighted the role of singlet oxygen ($1O_2$) and dissolved organic matter (DOM) in indirect photolysis. These parameters can strongly influence observed kinetics in natural waters, making direct photolysis, as studied here, a useful reference for evaluating the fundamental behavior of fluoroquinolones in more complex systems. Overall, our results fit coherently within the range of kinetic constants reported in recent literature while providing additional insight into the effect of pH and a direct comparison between OFX and NFX in river water. The combined analysis of photolysis kinetic parameters and fluorescence lifetimes (τ_F) reveals a direct relationship between **photochemical stability** and the **dynamics of excited states** of fluoroquinolones. OFX exhibits slower degradation and a longer fluorescence lifetime (**τ_F = 7.08 ns**) than NFX (**τ_F = 2.04 ns**), indicating a lower propensity for nonradiative decay and transition to the triplet state. This correlation between τ_F and kinetic constants (k, $t_{1/2}$) suggests that **fluorescence lifetime is a relevant photophysical indicator** for predicting the photostability of fluoroquinolones in aquatic environments. It provides a complementary approach linking fundamental spectroscopic properties to the environmental reactivity of the studied compounds.

4. Conclusion

UV-C photolysis provides valuable mechanistic insights into the environmental fate of fluoroquinolones. Photostability is influenced not only by pH but also by the excited-state dynamics and molecular speciation. OFX exhibits intrinsically higher photostability than NFX, as reflected by its longer fluorescence lifetime ($\tau F = 7.08$ ns), although in natural waters, environmental factors such as dissolved organic matter and reactive oxygen species can accelerate its degradation. The zero-order kinetics observed for OFX at acidic and basic pH are attributed to saturation of photon absorption sites, while zwitterionic forms of both antibiotics display enhanced photoreactivity due to favorable electronic structure and higher UV absorbance. Linking photophysical properties with kinetic behavior provides a predictive framework for understanding the persistence and photochemical treatment of pharmaceutical contaminants in aquatic environments, despite the higher energy of UV-C compared to solar irradiation.

Acknowledgements

We thank the UADB University for the mobility grant accorded to Abdourhamane Khonté and Diégane Sarr. We thank the UCAD University for the mobility grant accorded to Diène Diégane Thiaré.

Authors' Contributions

All authors contributed to the study conception and design. Material preparation and data collection were performed by Abdourahmane Khonté, Diène Diégane Thiaré, Jean-Pierre Bakhoum. Analysis were performed by Coura Dione, Ndeye Arame Diop, Pape Abdoulaye Diaw and Atanasse Coly. The first draft of the manuscript was written by Philippe Giamarchi All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement

Data are available upon request.

Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

References

[1] Carvalho, I.T. and Santos, L. (2016) Antibiotics in the Aquatic Environments: A Review of the European Scenario. *Environment International*, **94**, 736-757.

https://doi.org/10.1016/j.envint.2016.06.025

[2] Andersson, M.I. and MacGowan, A.P. (2003) Development of the Quinolones. *Journal of Antimicrobial Chemotherapy*, **51**, 1-11. https://doi.org/10.1093/jac/dkg212

[3] Hooper, D.C. and Jacoby, G.A. (2018) Topoisomerase Inhibitors: Fluoroquinolone Mechanisms of Action and Resistance. *Cold Spring Harbor Perspectives in Medicine*, **6**, a025320. https://doi.org/10.1101/cshperspect.a025320

[4] aus der Beek, T., Weber, F., Bergmann, A., Hickmann, S., Ebert, I., Hein, A., *et al.* (2016) Pharmaceuticals in the Environment—Global Occurrences and Perspectives. *Environmental Toxicology and Chemistry*, **35**, 823-835. https://doi.org/10.1002/etc.3339

[5] Larsson, D.G.J. and Flach, C. (2022) Antibiotic Resistance in the Environment. *Nature Reviews Microbiology*, **20**, 257-269. https://doi.org/10.1038/s41579-021-00649-x

[6] Mondal, B., Basak, S.S., Das, A., Sarkar, S. and Adak, A. (2024) UV-Based Degradation of Fluoroquinolone Antibiotic in Wastewater: Effects of Process Parameters, Identification of Degradation Products and Evaluation of Residual Toxicity. *Journal of the Institution of Engineers* (*India*): *Series A*, **105**, 1017-1028. https://doi.org/10.1007/s40030-024-00840-2

[7] Pretali, L., Fasani, E. and Sturini, M. (2022) Current Advances on the Photocatalytic Degradation of Fluoroquinolones: Photoreaction Mechanism and Environmental Application. *Photochemical & Photobiological Sciences*, **21**, 899-912. https://doi.org/10.1007/s43630-022-00217-z

[8] Tyutereva, Y.E., Snytnikova, O.A., Sheven, D.G., Fedunov, R.G., Yanshole, V.V., Grivin, V.P., *et al.* (2024) Mechanism of UV Photodegradation of Fluoroquinolone Antibiotic Ciprofloxacin in Aqueous Solutions. *Chemosphere*, **367**, Article 143643. https://doi.org/10.1016/j.chemosphere.2024.143643

[9] Joseph, N.K., Koshy, V.J., Aravind, U.K. and Aravindakumar, C.T. (2024) Phototransformation of Ofloxacin in Natural Aquatic Conditions: Impact of Indirect Photolysis on the Product Profile and Transformation Mechanism. *Chemosphere*, **361**, Article 142484. https://doi.org/10.1016/j.chemosphere.2024.142484

[10] Alhassani, A., Alnakshbandi, A.A. and Al-Nimer, M.S. (2020) The Effect of Ultraviolet-B Irradiation on the Photodegradation of Ciprofloxacin and Norfloxacin as Inhibitors of Bacterial DNA Replication and Cell Division in Urea Medium. *Cellular and Molecular Biology*, **66**, 51-55. https://doi.org/10.14715/cmb/2020.66.7.9

[11] Li, H., Wang, Z., Geng, J., Song, R., Liu, X., Fu, C., *et al.* (2025) Current Advances in UV-Based Advanced Oxidation Processes for the Abatement of Fluoroquinolone Antibiotics in Wastewater. *Chinese Chemical Letters*, **36**, Article 110138. https://doi.org/10.1016/j.cclet.2024.110138

[12] Stando, K., Zogornik, P., Kopiec, M., Pieszczek, M., Kowalska, K., Felis, E., *et al.* (2024) Degradation of Fluoroquinolones and Macrolides by Solar Light-Driven Heterogeneous Photocatalysis—Proposed Drug Transformation Pathways. *Journal of Photochemistry and Photobiology A*: *Chemistry*, **453**, Article 115651. https://doi.org/10.1016/j.jphotochem.2024.115651

[13] Lu, J., Ji, Y., Chovelon, J. and Lu, J. (2021) Fluoroquinolone Antibiotics Sensitized Photodegradation of Isoproturon. *Water Research*, **198**, Article 117136. https://doi.org/10.1016/j.watres.2021.117136

[14] Khonté, A., Kital, K., Bakhoum, J.P., Dione, L., Oyelakin, O., Thiaré, D.D., *et al.* (2026) Validated Micelle-Enhanced Spectrofluorimetric Determination of Serotonin in Human Urine. *Chemical Science International Journal*, **35**, 1-18.

https://doi.org/10.9734/csji/2026/v35i21022

[15] Khonté, A., Ba, S., Yatte, B.S., Diop, Y., Sarr, D., Thiaré, D.D., *et al.* (2025) Photodegradation Kinetics of Rimsulfuron in Senegalese Surface and Groundwater, and Determination of Its Herbicidal Activity. *Advances in Chemical Engineering and Science*, **15**, 47-59. https://doi.org/10.4236/aces.2025.152004

[16] Sturini, M., Speltini, A., Maraschi, F., Pretali, L., Profumo, A., Fasani, E., *et al.* (2012) Photodegradation of Fluoroquinolones in Surface Water and Antimicrobial Activity of the Photoproducts. *Water Research*, **46**, 5575-5582. https://doi.org/10.1016/j.watres.2012.07.043

[17] Ge, L., Chen, J., Zhang, S., Cai, X., Wang, Z. and Wang, C. (2010) Photodegradation of Fluoroquinolone Antibiotic Gatifloxacin in Aqueous Solutions. *Chinese Science Bulletin*, **55**, 1495-1500. https://doi.org/10.1007/s11434-010-3139-y

[18] Baran, W., Madej-Knysak, D., Klink, O. and Adamek, E. (2026) Environmental Impact of Fluoroquinolones and Their Photocatalytic Transformation Products: Degradation with Activated Sludge and in Surface Waters, Change in Antimicrobial Activity and Ecotoxicity. *International Journal of Molecular Sciences*, **27**, Article 2099. https://doi.org/10.3390/ijms27052099

[19] Liu, B., Chen, B., Zhang, B., Song, X., Zeng, G. and Lee, K. (2021) Photocatalytic Ozonation of Offshore Produced Water by TiO_2 Nanotube Arrays Coupled with UV-LED Irradiation. *Journal of Hazardous Materials*, **402**, Article 123456. https://doi.org/10.1016/j.jhazmat.2020.123456

[20] Lin, H., Lin, S., Awasthi, M.K., Wang, Y. and Xu, P. (2021) Exploring the Bacterial Community and Fermentation Characteristics during Silage Fermentation of Abandoned Fresh Tea Leaves. *Chemosphere*, **283**, Article 131234. https://doi.org/10.1016/j.chemosphere.2021.131234

[21] Favere, J., Buysschaert, B., Boon, N. and De Gusseme, B. (2020) Online Microbial Fingerprinting for Quality Management of Drinking Water: Full-Scale Event Detection. *Water Research*, **170**, Article 115353. https://doi.org/10.1016/j.watres.2019.115353

[22] Lu, Q., Qin, S., Wang, W., Wang, Q. and Kang, S. (2023) Geochemistry of Late Permian Coals from the Yueliangtian Coal Deposit, Guizhou: Evidence of Sediment Source and Evaluation on Critical Elements. *Science of The Total Environment*, **856**, Article 159123. https://doi.org/10.1016/j.scitotenv.2022.159123

[23] Kümmerer, K. (2009) Antibiotics in the Aquatic Environment—A Review—Part I. *Chemosphere*, **75**, 417-434. https://doi.org/10.1016/j.chemosphere.2008.11.086

[24] Lin, X., Zhou, W., Li, S., Fang, H., Fu, S., Xu, J., *et al.* (2023) Photodegradation of Sulfamethoxazole and Enrofloxacin under UV and Simulated Solar Light Irradiation. *Water*, **15**, Article 517. https://doi.org/10.3390/w15030517

[25] Polishchuk, A., Emelina, T., Karaseva, E., Cramariuc, O., Chukharev, V. and Karasev, V. (2013) Photochemical Behavior and Photolysis of Protonated Forms of Levofloxacin. *Photochemistry and Photobiology*, **90**, 79-84. https://doi.org/10.1111/php.12152

[26] Feng, Y., Yang, Y., Huang, L., He, Y. and Zhang, Y. (2026) Photolysis of Fluoroquinolone Antibiotics in Aquatic Environments: Mechanisms, Influencing Factors and Environmental Implications—A Mini Review. *Royal Society Open Science*, **13**, Article 250891. https://doi.org/10.1098/rsos.250891

[27] Andreozzi, R., Raffaele, M. and Nicklas, P. (2003) Pharmaceuticals in STP Effluents and Their Solar Photodegradation in Aquatic Environment. *Chemosphere*, **50**, 1319-1330. https://doi.org/10.1016/s0045-6535(02)00769-5

[28] Polianciuc, S.I., Gurzău, A.E., Kiss, B., Ştefan, M.G. and Loghin, F. (2020) Antibiotics in the Environment: Causes and Consequences. *Medicine and Pharmacy Reports*, **93**, 231-240. https://doi.org/10.15386/mpr-1742

[29] Wammer, K.H., Korte, A.R., Lundeen, R.A., Sundberg, J.E., McNeill, K. and Arnold, W.A. (2013) Direct Photochemistry of Three Fluoroquinolone Antibacterials: Norfloxacin, Ofloxacin, and Enrofloxacin. *Water Research*, **47**, 439-448. https://doi.org/10.1016/j.watres.2012.10.025

[30] Fasani, E., Profumo, A. and Albini, A. (1998) Structure and Medium-Dependent Photodecomposition of Fluoroquinolone Antibiotics. *Photochemistry and Photobiology*, **68**, 666-674. https://doi.org/10.1111/j.1751-1097.1998.tb02527.x

[31] Liu, S., Cui, Z., Bai, Y., Ding, D., Yin, J., Su, R., *et al.* (2023) Indirect Photodegradation of Ofloxacin in Simulated Seawater: Important Roles of DOM and Environmental Factors. *Frontiers in Marine Science*, **10**, Article ID: 1132216. https://doi.org/10.3389/fmars.2023.1132216

[32] Snowberger, S., Adejumo, H., He, K., Mangalgiri, K.P., Hopanna, M., Soares, A.D., *et al.* (2016) Direct Photolysis of Fluoroquinolone Antibiotics at 253.7 Nm: Specific Reaction Kinetics and Formation of Equally Potent Fluoroquinolone Antibiotics. *Environmental Science & Technology*, **50**, 9533-9542. https://doi.org/10.1021/acs.est.6b01794

[33] Guo, H., Gao, N., Chu, W., Li, L., Zhang, Y., Gu, J., *et al.* (2013) Photochemical Degradation of Ciprofloxacin in UV and UV/H_2O_2 Process: Kinetics, Parameters, and Products. *Environmental Science and Pollution Research*, **20**, 3202-3213. https://doi.org/10.1007/s11356-012-1229-x

[34] Ahmad, I., Bano, R., Musharraf, S.G., Sheraz, M.A., Ahmed, S., Tahir, H., *et al.* (2015) Photodegradation of Norfloxacin in Aqueous and Organic Solvents: A Kinetic Study. *Journal of Photochemistry and Photobiology A*: *Chemistry*, **302**, 1-10. https://doi.org/10.1016/j.jphotochem.2015.01.005

[35] Bobu, M., Yediler, A., Siminiceanu, I., Zhang, F. and Schulte-Hostede, S. (2013) Comparison of Different Advanced Oxidation Processes for the Degradation of Two Fluoroquinolone Antibiotics in Aqueous Solutions. *Journal of Environmental Science and Health*, *Part A*, **48**, 251-262. https://doi.org/10.1080/10934529.2013.726805

[36] Cuerda-Correa, E.M., Alexandre-Franco, M.F. and Fernández-González, C. (2019) Advanced Oxidation Processes for the Removal of Antibiotics from Water. an Overview. *Water*, **12**, Article 102. https://doi.org/10.3390/w12010102

[37] Zhang, Z., Xie, X., Yu, Z. and Cheng, H. (2019) Influence of Chemical Speciation on Photochemical Transformation of Three Fluoroquinolones (FQS) in Water: Kinetics, Mechanism, and Toxicity of Photolysis Products. *Water Research*, **148**, 19-29. https://doi.org/10.1016/j.watres.2018.10.027

[38] Niu, X., Busetti, F., Langsa, M. and Croué, J. (2016) Roles of Singlet Oxygen and Dissolved Organic Matter in Self-Sensitized Photo-Oxidation of Antibiotic Norfloxacin under Sunlight Irradiation. *Water Research*, **106**, 214-222. https://doi.org/10.1016/j.watres.2016.10.002

[39] Zhang, X., Li, J., Fan, W., Yao, M., Yuan, L. and Sheng, G. (2019) Enhanced Photodegradation of Extracellular Antibiotic Resistance Genes by Dissolved Organic Matter Photosensitization. *Environmental Science & Technology*, **53**, 10732-10740. https://doi.org/10.1021/acs.est.9b03096