

Review

Photodegradation of hydroxylated *N*-heteroaromatic derivatives in natural-like aquatic environments

A review of kinetic data of pesticide model compounds

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Abstract

In the present review, the results published by our group and others related with the study of the kinetic behavior and, in some cases, the mechanism of the dye-promoted photooxygenation of several hydroxypyridines, hydroxyquinolines and hydroxypyrimidines—some of them with the basic molecular structures of known pesticides, and of a few non-hydroxylated model compounds, are compiled and discussed. The main aim was to examine the experimental conditions that maximize the photodegradation efficiencies of all these compounds, under dye-sensitized photooxidation conditions similar to those frequently found in nature, with a natural dye sensitizer such as riboflavin (vitamin B₂), a pigment habitually present in natural waters. The usual mechanism of action of this compound is rather complex, in many cases with the concurrent involvement of the oxidative species singlet molecular oxygen (O₂(¹Δ_g)) and superoxide radical anion. In order to simplify the study of the processes, the results found using the synthetic dye Rose Bengal (RB), a sensitizer that generates O₂(¹Δ_g) with high efficiency, are also discussed. RB and similar O₂(¹Δ_g)-generators could be used for the efficient non-natural photodegradation of related pesticides in aqueous solutions under controlled conditions.

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Keywords: Pesticide model compounds; Photodegradation; Sensitized photooxidation; Singlet molecular oxygen; Superoxide radical anion

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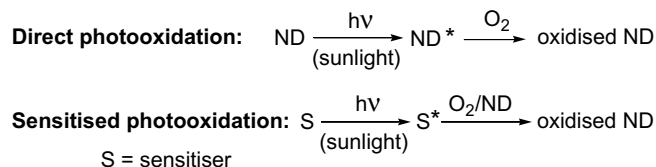
1. Introduction

Many agricultural pesticides of profuse use have molecular structures with a six-membered nitrogen-containing aromatic heterocycle (ND) (Tomlin, 1994), and significant amounts of these compounds are contaminants of surface waters and soils. The knowledge of the persistence of ND pesticides in the environment is very important for their use in crop protection and other practical applications. Consequently, both the thermal and the photochemical pathways of degradation of such contaminants are topics of growing interest (Alseberg et al., 1994; García, 1994). In particular, their photoinduced degradation to non-toxic products under natural conditions—i.e. in aerated water solution and under sunlight irradiation—has been tested with variable success, and the reactions involved have been studied in order to know more about the natural photochemical decay of all these substances (Wilkinson et al., 1995; Burrows et al., 2002). The photochemical decay can become the most important degradation pathway, in special in sunny countries and under favorable environmental conditions. When the contaminant absorbs light in the near-UV zone, it can be degraded in an aqueous environment through the direct oxidation of its electronically excited state with the dissolved oxygen, or through the reaction with the oxidant species singlet molecular oxygen, $O_2(^1\Delta_g)$, and/or superoxide anion, $O_2^{\cdot-}$, generated by en-

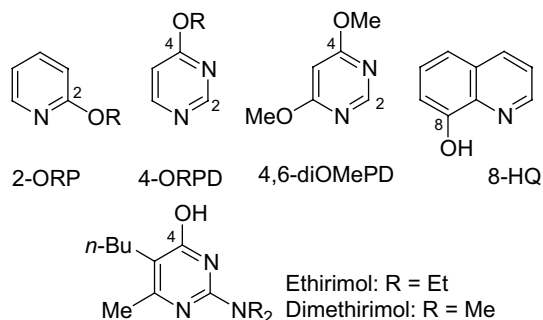
ergy transfer or electron transfer, respectively, from the electronically excited contaminant to ground state oxygen (Scheme 1). On the other hand, when the contaminant does not absorb any wavelength of the sunlight, the degradation can also be carried out through $O_2(^1\Delta_g)/O_2^{\cdot-}$ pathways if another colored (or even non-colored) sensitizer, able to generate these oxygen species, is present in the medium.

Few works have been formerly devoted to the study of the behavior of ND compounds as physical and/or chemical $O_2(^1\Delta_g)$ quenchers (Dalle et al., 1972; Young and Brewer, 1976; Larson and Marley, 1984), possibly because of their usually low chemical reactivity towards this oxygen species. Nevertheless, it is known that in some cases the photooxidative reactivity can be considerably enhanced by adequate choice of experimental conditions, such as type of dye sensitizer, solvent polarity, pH of the medium, presence of detergents, etc. The presence of electron-releasing groups such as OH or NH_2 in the molecule of the ND pesticide should increase the reactivity with the electrophilic reagent $O_2(^1\Delta_g)$.

Only the commercial pyrimidine fungicides ethirimol and dimethirimol have a formal OH-group in the aromatic heterocycle (Scheme 2), although in aqueous solution the presence of the corresponding 4(3*H*)-pyrimidinone tautomer cannot be neglected. On the contrary, many ND pesticides have an *O*-substituted



Scheme 1. Possible photooxidation pathways of ND pesticides.



Scheme 2. Some basic structures of OR–ND pesticides.

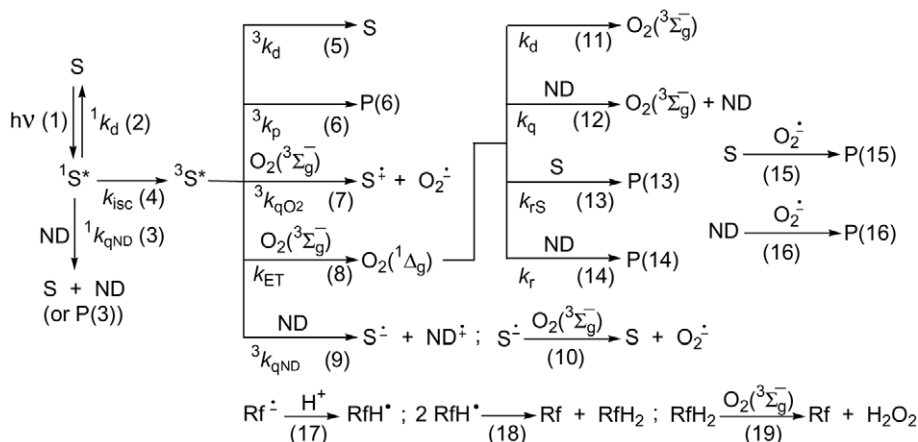
group (OR) bound to the heterocycle (Tomlin, 1994). OR–ND commercial pesticides in current use are 2-OR pyridines (2-ORP, R = alkyl, substituted alkyl, substituted aryl; or OR = dimethyl phosphorothioate, diethyl phosphorothioate), 4-OR pyrimidines (4-ORPD, OR = dimethylsulfamate, dimethylcarbamate, diethyl phosphorothioate), 4,6-dimethoxypyrimidines (4,6-diOMePD), and some 8-OH quinoline derivatives (8-HQ) (sulfate, Cu(II) quelate, ether ester 8-OR, with R = CH₂CO₂Mexyl). Under environmental conditions, OR–ND pesticides could undergo hydrolysis to the corresponding compounds with free OH-group (OH–ND), which are much more sensitive to photodegradation via O₂(¹Δ_g)-photooxidation, in special in alkaline media. On the other hand, a possible way of modulating the degradation via O₂(¹Δ_g) of a particular ND pesticide, and hence its permanence in the natural environment, could be by the introduction of an activating substituent, such as an OH-group, in the *N*-heterocycle of the molecule (Wilkinson et al., 1993).

In the present review, we compile and discuss the results published by our group and others related with

the study of the kinetic behavior and, in some cases, the mechanism of the dye-promoted photooxygenation of several hydroxypyridines (HPs), hydroxyquinolines (HQs) and hydroxypyrimidines (HPDs)—some of them with the basic molecular structures of known pesticides, and of a few non-hydroxylated model compounds. The main aim was to examine the experimental conditions that maximize the photodegradation efficiencies of all these ND compounds, under dye-sensitized photooxidation conditions similar to those frequently found in nature, with a natural dye sensitizer such as riboflavin (Rf) (vitamin B₂), a pigment usually present in natural waters (Benassi et al., 1967; Chacon et al., 1988). As the usual mechanism of action of this dye is rather complex, in many cases with the concurrent involvement of the oxidative species O₂(¹Δ_g) and O₂^{•−}, we first discuss the results found using the synthetic dye Rose Bengal (RB), a sensitizer that generates O₂(¹Δ_g) with high efficiency (Neckers, 1989; Amat-Guerri et al., 1990), simplifying in this way the study of the photooxidation processes. On the other hand, RB and similar O₂(¹Δ_g)-generators could be used for the efficient non-natural photodegradation of ND pesticides in aqueous solutions under controlled conditions. A review comprising the first results of our group on the former subjects has been published (García and Amat-Guerri, 2001). A general review on the photodegradation mechanism of many known pesticides, by both direct photolysis and photosensitization, has been also published (Burrows et al., 2002).

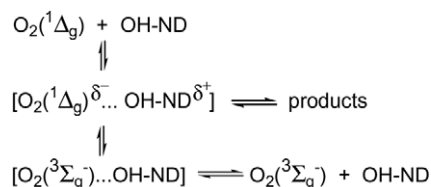
2. The sensitized photooxidation process

The main possible processes that can take place when a solution containing a ND compound and a dye sensitizer, S, is irradiated with visible light in the presence of oxygen are shown in Scheme 3. The prevalence of any of

Scheme 3. Main possible interactions in the visible-light aerobic irradiation of a six-membered aromatic *N*-heterocycle (ND) and a dye sensitizer (S), such as Rose Bengal (RB) or riboflavin (Rf). P denotes a reaction product.

them usually depends on the experimental conditions and on the involved ND and S compounds. The initially generated excited singlet state of the sensitizer ($^1S^*$, process (1)) can decay to ground state S (2), can be quenched by ND (3), or can produce excited triplet S ($^3S^*$) (4). $^3S^*$ can decay to ground state S (5), can yield products (6), can be quenched by ground state oxygen, $O_2(^3\Sigma_g^-)$, generating $O_2^{\cdot-}$ by electron transfer (7), and $O_2(^1\Delta_g)$ by energy transfer (8), or can accept an electron from ND yielding semireduced S ($S^{\cdot-}$) (9). $S^{\cdot-}$ can also generate $O_2^{\cdot-}$ by electron transfer to oxygen (10). On the other hand, $O_2(^1\Delta_g)$ can be physically quenched either by the medium (11) or by ND (12), or can react either with S (13) or with ND (14). Reaction (14), with reactive rate constant k_r , is the main pathway of disappearance of ND in $O_2(^1\Delta_g)$ -mediated processes. In parallel, the generated $O_2^{\cdot-}$ can chemically react with S (15) or with ND (16). When the dye RB is employed as a sensitizer, the photogeneration of $O_2(^1\Delta_g)$ through processes (4) and (8) is usually very efficient, with quantum yields close to 0.9 (Neckers, 1989; Amat-Guerri et al., 1990). On the other hand, when riboflavin (Rf) is employed instead, both $O_2(^1\Delta_g)$ (process (8)) and $O_2^{\cdot-}$ (process (7)) are photogenerated, with reported quantum yields in water of 0.49 (Wilkinson et al., 1993) and 0.009 (Krishna et al., 1991). Hence, the generation of the species $S^{\cdot+}$ and $O_2^{\cdot-}$ via process (7) is negligible in kinetic terms. Rf is also a moderate quencher of $O_2(^1\Delta_g)$, with an overall rate constant, $k_{rRf} = k_{qRf} + k_{rRf}$, for the physical and chemical quenching (processes (12), with Rf instead of ND, and (13), with S = Rf) of $6 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ (Chacon et al., 1988). Nevertheless, in the presence of an adequate substrate such as ND, $^3Rf^*$ can give rise, via $Rf^{\cdot-}$ (process (9)), to $O_2^{\cdot-}$ (process (10)). Semireduction of $^3Rf^*$ to $Rf^{\cdot-}$ has been proposed in order to explain the photoinitiation of vinyl polymerizations with Rf (Bertolotti et al., 1999), as well as the interaction of ascorbic acid with the Rf-chromophore radical from flavin-mononucleotide (Heelis et al., 1981). In the presence of proton donating species, the generation of Rf neutral radical (RfH^{\cdot} , process (17)) should occur, with a pK value of 8.3 (Lu et al., 2000; Lu et al., 2004). Nevertheless, although it is known that the reaction of ground state oxygen with RfH^{\cdot} is much slower than with $Rf^{\cdot-}$ (process (10)), the bimolecular decay of RfH^{\cdot} through a disproportionation reaction can yield Rf and fully reduced Rf (RfH_2) (process (18)), which in the presence of $O_2(^3\Sigma_g^-)$ can be reoxidized giving Rf and H_2O_2 (process (19)) (Lu et al., 2000). In any case, reactions (10) and (18) constitute pathways for $O_2^{\cdot-}$ and H_2O_2 production and Rf regeneration, being both oxygenated species good candidates to react with ND compounds.

Regarding $O_2(^1\Delta_g)$ -mediated photooxidations (process (14)), their efficiency is correctly evaluated through the determination of the photooxidation quantum efficiency, $\phi_r = k_r[ND]/(k_q + k_t[ND])$ (Bocco et al., 1994;



Scheme 4. Mechanism of the interaction between $O_2(^1\Delta_g)$ and OH-ND.

García, 1994). The ϕ_r value so determined takes into account the simultaneous effect of the physical and chemical interactions, being the k_q contribution usually interpreted in practical terms as a form of self-protection against $O_2(^1\Delta_g)$ -mediated photooxidations. Nevertheless, the ϕ_r value depends on the concentration of the photooxidizable substrate ([ND] in the present case), which is particularly difficult to estimate in complex systems such as contaminated environments. On the other hand, no relevant information about these photoreactions can be obtained from the straightforward analysis of isolated k_t and k_r values (García, 1994). A simpler and more useful approach is the evaluation of the k_r/k_t ratio, which can be envisaged as the fraction of the overall interaction $O_2(^1\Delta_g)$ -substrate that leads to effective chemical transformation. In the present review this ratio will be used for the discussion of results.

When the kinetics of $O_2(^1\Delta_g)$ -mediated photooxidations of aromatic compounds with free OH-group is studied in different media, two common features are generally observed (García, 1994): (a) the overall $O_2(^1\Delta_g)$ quenching is favored—i.e. the k_t value increases—with the increase of the solvent polarity; and (b) k_t values of the species with the OH-group in ionized form are ca. two orders of magnitude higher than those of the un-ionized one, and the reactive quenching of $O_2(^1\Delta_g)$ by the latter is hardly observed. These features have been rationalized on the basis of a photooxidation mechanism involving an intermediate complex with partial charge-transfer character, an explanation formerly used to account for the well known medium dependence of the kinetic photooxidation behavior of phenols (Thomas and Foote, 1978; Foote, 1984; Luiz et al., 1993; Bocco et al., 1994) and other aromatic compounds with free OH-group (Pajares et al., 1998; Amat-Guerri et al., 1999). In the cases of the OH-ND compounds herein studied, the proposed mechanism of interaction via said intermediate is shown in Scheme 4.

3. Photooxidations sensitized by Rose Bengal

3.1. Hydroxypyridines

The kinetics of the dye-sensitized photooxygenation of a series of mono- and dihydroxypyridines has been

studied in different media (Pajares et al., 1998, 2002; Amat-Guerri et al., 1999). The structures of all the studied HP compounds are shown in Table 1. Rate constants k_t and k_r , determined for the reactive dyes by time-resolved $O_2(^1\Delta_g)$ -phosphorescence detection and polarographic methods, were in the range 10^6 – 10^8 $M^{-1} s^{-1}$. When aerated solutions of any of these OH-ND compounds, in water or in mixtures acetonitrile/water or acetonitrile/methanol, were irradiated in the presence of RB, in most cases important absorbance changes were observed in their respective absorption spectra (representative changes are shown in Fig. 1), and oxygen was consumed during the photoirradiation (see example in Fig. 2, main). These experimental results, in conjunction with the quenching of the time-resolved phosphorescence signal of $O_2(^1\Delta_g)$ by each HP compound (example in Fig. 2, inset), constitute unambiguous evidence of $O_2(^1\Delta_g)$ -mediated photooxidation processes. The values of the ratio k_r/k_t were in the range 0.02–1, in the cases where reaction was observed, with values significantly higher in alkaline aqueous media. In monohydroxylated pyridines, the position of the OH-group plays a key role in the efficiency of their interaction with $O_2(^1\Delta_g)$. In 2-HP and 4-HP, the presence of the tautomeric oxo form (Scheme 5), much less aromatic than the hydroxy form (Boulton and McKillop, 1984; Johnson, 1984) and, hence, much less reactive towards the well known electrophilic reagent $O_2(^1\Delta_g)$, drastically suppresses the interaction with the oxidative species. On the contrary, the OH-ionization greatly enhances the photooxidative process, as shown in Fig. 3 for the case of 3-HP. An excellent concordance can be observed for 3-HP between the inflection point of the curve k_r vs. pH and the pK_a value of 3-HP, 8.72 (described by Grachev et al., 1973). Besides, the increase of the k_r values with the solvent polarity is in accord with the proposed mechanism through the excited complex shown in Scheme 4.

The hydroxypyridines shown in Table 1 are in most cases efficient physical and/or chemical scavengers of $O_2(^1\Delta_g)$, but not their non-hydroxylated parent compound pyridine, which shows a k_t value in CCl_4 solution of 2×10^3 $M^{-1} s^{-1}$ (Young and Brewer, 1976). This different behavior has been also found in phenols (Okanioto et al., 1982; Luiz et al., 1993), polyhydroxybenzenes (Mártire et al., 1991) and hydroxybiphenyls (Mártire et al., 1993), with regard to their corresponding non-hydroxylated compounds (Wilkinson et al., 1995).

Of the three isomeric HP, 3-HP shows the highest k_r value, i.e. is the most susceptible towards $O_2(^1\Delta_g)$ -mediated photooxidation. The results found for several 2-substituted 3-HPs indicate that the k_t value increases with electron-releasing substituents at position 2, as well as in water or in alkaline media, pointing to a quenching process through the mentioned polar complex [$O_2(^1\Delta_g)^{\delta-} \cdots HP^{\delta+}$]. All these 3-HPs are photooxidised,

showing 2-methyl-3-hydroxypyridine (2-Me-3-HP) the highest k_r/k_t ratio.

The products of the photooxidation in water of 3-HP have been analyzed by GC/MS, and products from the pyridine ring cleavage, as well as 2,3-dihydroxypyridine (2,3-DHP), have been detected (Amat-Guerri et al., 1999). All can be derived from a 1,2-dioxetane intermediate formed by $O_2(^1\Delta_g)$ addition to the 2,3-positions of the pyridine ring (Scheme 6).

The kinetics of the RB-sensitized photooxidation of 2,3-DHP and 2,4-dihydroxypyridine (2,4-DHP) is somewhat different. These compounds present different tautomeric and ionization states, depending on the pH of the medium (Scheme 7) (Pajares et al., 2002). The ratios k_r/k_t found (Table 1) in water at pH 5, pH 11 and pH 14, and in the mixture MeCN/water 4:1 v/v, with and without 10 mM KOH, indicate that both DHPs are efficiently oxidized with $O_2(^1\Delta_g)$ over an extended pH range. Nevertheless, if these DHPs are compared with HP compounds, only 2,3-DHP reacts with higher efficiency. In a general sense, the increase of pH favors the overall interaction $O_2(^1\Delta_g)$ -DHP, although this interaction does not correlate with the importance of the photooxidation reaction. In pH 5 medium or in the mixture MeCN/water 4:1, solvents where the respective un-ionized 2-pyridone forms predominate, only 2,3-DHP is photooxidised, whereas 2,4-DHP slightly deactivates $O_2(^1\Delta_g)$ only in a physical fashion. The highest k_r/k_t ratios are reached in pH 11 water solution or in alkalized MeCN/water, where the respective mono-ionized 2-pyridone forms predominate. In addition, in pH 14 water solution both di-ionized dihydroxypyridines show the highest k_t values, but lower relative reactivity than in pH 11 water solution.

3.2. Hydroxyquinolines

8-Hydroxyquinoline (8-HQ) (oxine) and some of their derivatives, including their quelates and salts with several metals, have shown cytotoxic (Shen et al., 1999a,b), antibacterial (Faizi et al., 1997; Patel et al., 1997; Valli et al., 2000; Murugasu-Oei and Dick, 2001), antifungal (Barboiu et al., 1996; Nicoletti et al., 1999a,b), and antimalarial (Scheibel and Rodriguez, 1989) activity. Their strong antibacterial properties have promoted their use as preservatives of pharmaceutical formulations and cosmetic products. All these activities and uses have prompted some studies on its thermal and photochemical stability. The kinetics of the thermal oxidation of 8-HQ to quinoline-5,8-quinone using pyridinium dichromate has been formerly reported (Palaniappan et al., 1998), and the dye-sensitized photooxidation of 8-HQ has been used for the preparative synthesis of said quinone with good yield (Amarasekara, 1999; Cossy and Belotti, 2001). On the other hand, several derivatives of 4-hydroxyquinoline (4-HQ) have also

Table 1
Rate constants ($M^{-1} s^{-1}$) for overall (k_t) and reactive (k_r) quenching of $O_2(^1\Delta_g)$ (from Rose Bengal sensitization) by hydroxypyridines (HP) in different solvents

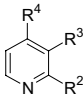
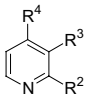
Compound				Solvent ^a	$k_r/10^{8b,c}$	$k_r/10^{8c}$	k_r/k_t
	R ²	R ³	R ⁴				
2-HP	OH	H	H	Water	NQ	NQ	~0
				Water, pH 11	1.23	0.20	0.16
				MeCN/MeOH 9:1	NQ	NQ	~0
				MeCN/MeOH 9:1 + KOH	1.45	0.03	0.02
3-HP	H	OH	H	Water	0.39	0.26	0.66
				Water, pH 11	2.60	2.60	1.00
				MeCN/MeOH 9:1	2.10	NQ	~0
				MeCN/MeOH 9:1 + KOH	2.80	0.81	0.32
				MeCN/water 4:1	0.037	0.016	0.43
				MeCN/water 4:1 + NaOH	2.0	1.31	0.65
4-HP	H	H	OH	Water	NQ	NQ	~0
				Water, pH 11	NQ	NQ	~0
				MeCN/MeOH 9:1	NQ	NQ	~0
				MeCN/MeOH 9:1 + KOH	NQ	NQ	~0
2-Me-3-HP	Me	OH	H	Water	0.52	0.52	1.00
				Water, pH 11	3.10	2.8	0.90
				MeCN/water 4:1	0.08	0.033	0.41
				MeCN/water 4:1 + NaOH	2.80	2.05	0.73
2-Am-3-HP	NH ₂	OH	H	Water	3.90	1.35	0.34
				Water, pH 11	6.60	2.9	0.44
				MeCN/water 4:1	0.99	0.29	0.29
				MeCN/water 4:1 + NaOH	3.20	1.1	0.34
2-Cl-3-HP	Cl	OH	H	Water	0.64	0.12	0.18
				Water, pH 11	2.90	1.7	0.58
				MeCN/water 4:1	0.25	0.24	0.96
				MeCN/water 4:1 + NaOH	1.86	0.99	0.53
2-Br-3-HP	Br	OH	H	Water	1.49	0.21	0.14
				Water, pH 11	1.56	1.56	1.00
				MeCN/water 4:1	0.33	0.23	0.69
				MeCN/water 4:1 + NaOH	2.36	0.60	0.25
2-C-3-HP	CO ₂ H	OH	H	Water	0.014	NQ	~0
				Water, pH 11	0.65	0.60	0.92
				MeCN/water 4:1	0.011	0.002	0.18
				MeCN/water 4:1 + NaOH	1.03	0.32	0.31
2-CA-3-HP	CONH ₂	OH	H	Water	0.073	0.039	0.53
				Water, pH 11	1.00	0.70	0.70
				MeCN/water 4:1	0.012	0.007	0.58
				MeCN/water 4:1 + NaOH	1.16	0.44	0.38
2,3-DHP	OH	OH	H	Water, pH/pD 5	3.40	0.51	0.15
				Water, pH/pD 11	5.60	3.55	0.63
				Water, pH/pD 14	6.80	1.0	0.14
				MeCN–water 4:1	0.70	0.71	1.01
				MeCN–water 4:1 + KOH	1.70	1.68	0.99

Table 1 (continued)

Compound				Solvent ^a	$k_t/10^{8b,c}$	$k_t/10^{8c}$	k_t/k_t
	R ²	R ³	R ⁴				
2,4-DHP	OH	H	OH	Water, pH/pD 5	0.008	NQ	~0
				Water, pH/pD 11	0.05	0.048	0.96
				Water, pH/pD 14	0.08	0.01	0.12
				MeCN/water 4:1	NQ	NQ	~0
				MeCN/water 4:1 + KOH	0.04	0.037	0.93

Estimated relative error 10%. Data taken from Amat-Guerri et al. (1999) and Pajares et al. (1998, 2002).

^a pH 11 water solutions made by adding KOH or NaOH; MeCN/MeOH 9:1 v/v + KOH (10 mM) solutions made by adding KOH in MeOH; MeCN/water 4:1 v/v + NaOH (10 mM) made by diluting a 50 mM NaOH solution in water with MeCN.

^b k_t was determined in D₂O solution, non buffered or at pD11.

^c NQ: no quenching or no reaction was observed up to concentration 5 mM.

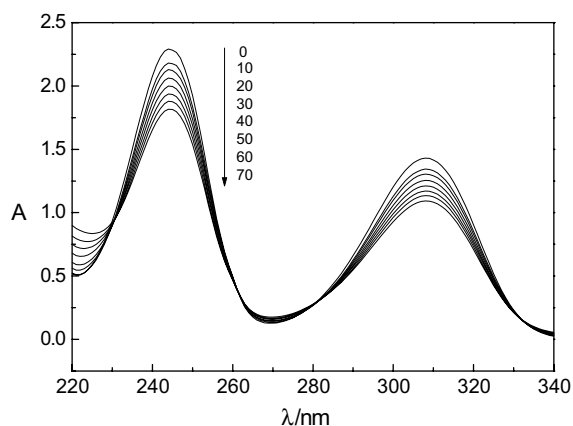


Fig. 1. Spectral changes in the Rose Bengal-sensitized photooxidation of 2-amino-3-hydroxypyridine (2-Am-3-HP) in pH 11 aqueous solution. Numbers on the spectra are irradiation times in seconds. Adapted from Amat-Guerri et al. (1999).

demonstrated different types of bioactivity (Sircar et al., 1992; Vo et al., 1993; Kayirere et al., 1998).

When solutions of 8-HQ, in water or in the organic solvent mixture MeCN/MeOH 9:1, were irradiated with visible light in the presence of RB, important changes were observed in the absorption spectra (Pajares et al., 1998). The changes were totally suppressed in the absence of dissolved molecular oxygen, as well as in the

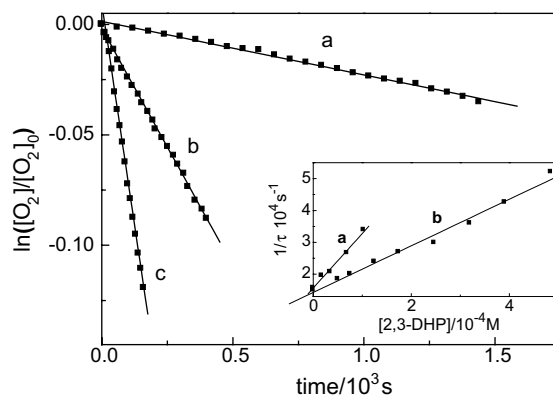
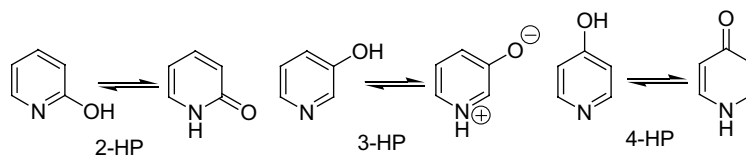


Fig. 2. First order plots for oxygen uptake upon Rose Bengal-sensitized photooxidation of 2,4-dihydroxypyridine (2,4-DHP) (a), furfuryl alcohol (b), and 2,3-dihydroxypyridine (2,3-DHP) (c), all 0.5 mM in pH 11 aqueous solution. $[O_2]$ and $[O_2]_0$: dissolved molecular oxygen concentrations at times $t = t$ and $t = 0$, respectively. Inset: Stern–Volmer plots for the quenching of $O_2(^1\Delta_g)$ phosphorescence by 2,3-DHP in MeCN/water 4:1 v/v plus 10 mM KOH (a), and in MeCN/water 4:1 v/v (b). Adapted from Pajares et al. (2002).

presence of 10 mM NaN₃, and were comparatively faster, at the same irradiation fluences, when H₂O was replaced by D₂O, clearly indicating $O_2(^1\Delta_g)$ -mediated (Type II) processes. No photoreaction was observed in the irradiation of 4-HQ in the former solvents (Table 2)



Scheme 5. Tautomeric equilibria in hydroxypyridines.

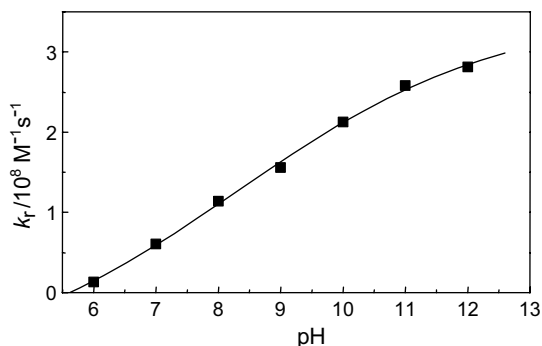
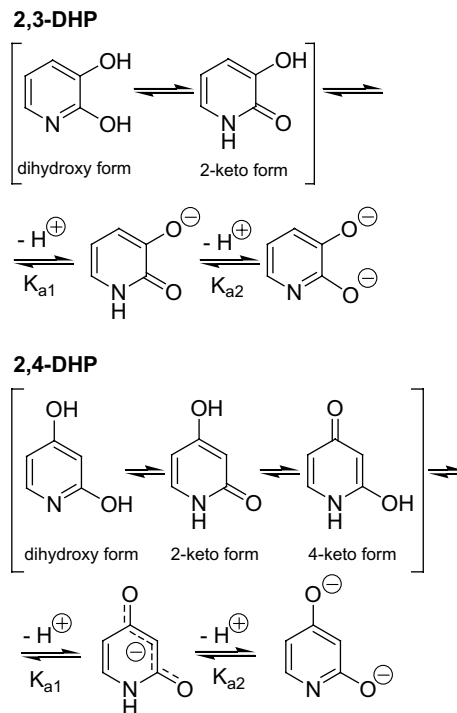


Fig. 3. Rose Bengal-sensitized photooxidation of 3-hydroxypyridine (3-HP). Dependence of the reactive rate constant, k_r , on the pH of the aqueous solution. Adapted from García and Amat-Guerri (2001).

(Pajares et al., 1998). In the presence of alkali, the reactivity of both HQs increased due to the ionization of the OH group (representative spectral changes for 8-HQ are shown in Fig. 4), as in the case of the related HPs. The highest k_r/k_t ratios were found in pH 11 water: 0.29 for 4-HQ, and 0.40 for 8-HQ.

In 4-HQ, the un-ionized non-photooxidizable 4-oxo tautomer predominates in acidic or neutral solvents, as in the case of 4-HP, whereas in 8-HQ the OH form is in equilibrium with the *N*-protonated zwitterionic tautomer (Scheme 8) (Johnson, 1984), and the reaction of $\text{O}_2(^1\Delta_g)$ with 8-HQ is comparatively favored.

For 8-HQ in the solvent mixture MeCN/MeOH 9:1, a k_t value of $0.015 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ has been found by TRPD methods (Pajares et al., 1998). This value is two orders of magnitude lower than the reported k_t value for the same compound in CHCl_3 solution (Larson and Marley, 1984), determined by the Carlsson method (Carlsson et al., 1974): $1.1 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$. The latter value must likely be overestimated because of the employment of rubrene with the double function of sensitizer and sacrificial substrate, thus overlooking the possible interaction

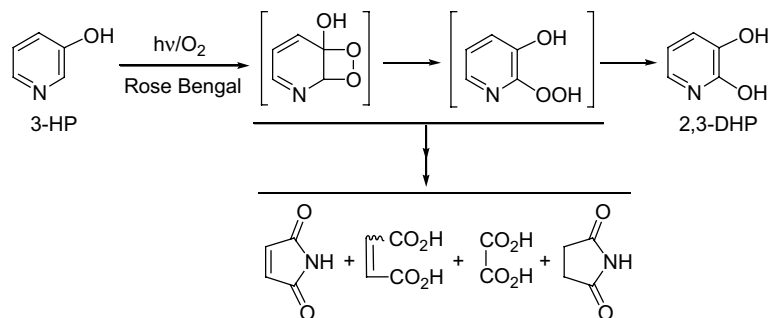


Scheme 7. Accepted tautomeric and ionized forms of 2,3-DHP and 2,4-DHP.

of excited singlet and/or triplet rubrene with the substrate (Gspöner et al., 1987).

3.3. Hydroxypyrimidines

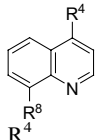
The kinetics of the sensitized photooxidation of the pyrimidine fungicides ethirimol, dimethirimol (Scheme 2) and four analogous pyrimidines has been reported, and the overall rate constants k_t have been evaluated in solution in water or chloroform (Harkness and Wells, 1981; Dixon and Wells, 1983). However, as pointed above, in terms of substrate photodegradation this



Scheme 6. Detected products and possible mechanism, for their formation in the Rose Bengal-sensitized photooxidation of 3-HP.

Table 2

Rate constants ($M^{-1} s^{-1}$) for overall (k_t) and reactive (k_r) quenching of $O_2(^1\Delta_g)$ (from Rose Bengal sensitization) by 4-hydroxyquinoline (4-HQ) and 8-hydroxyquinoline (8-HQ) in different media

Compound			Solvent	$k_t/10^{8a,b}$	$k_r/10^{8b}$	k_r/k_t
4-HQ	OH	H	Water pH 6	NQ	NQ	~0
			Water pH 11	0.90	0.26	0.29
			MeCN/MeOH 9:1	NQ	NQ	~0
			MeCN/MeOH 9:1 + KOH	0.16	0.030	0.19
8-HQ	H	OH	Water pH 6	0.23	0.08	0.35
			Water pH 11	4.20	1.70	0.40
			MeCN/MeOH 9:1	0.015	<0.001	<0.001
			MeCN/MeOH 9:1 + KOH	4.68	0.052	0.01

Data taken from Pajares et al. (1998).

^a k_t was determined in D_2O (pD 6 or pD 11) solution.

^b NQ: no quenching or no reaction was observed up to concentration 5 mM.

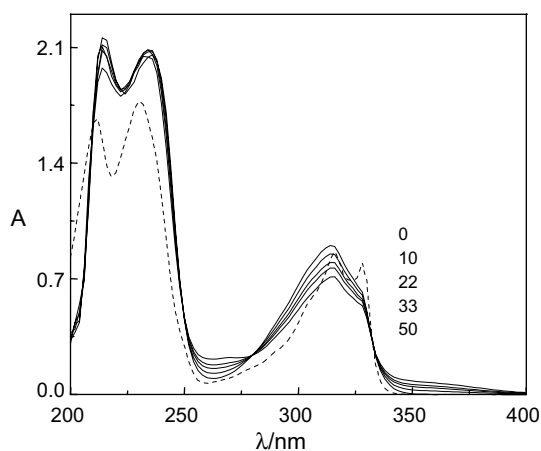
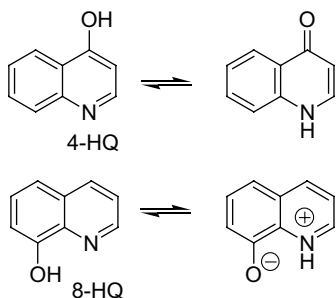


Fig. 4. Spectral evolution upon Rose Bengal-sensitized photooxidation of 8-hydroxyquinoline (8-HQ) in pH 11 aqueous solution (full lines). Numbers on the spectra are irradiation times in seconds. For comparison, the spectrum of 8-HQ in pH 6 aqueous solution is included (dashed line). Adapted from Pajares et al. (1998).



Scheme 8. Tautomeric equilibria in 4-HQ and 8-HQ.

constant provides only limited kinetic information about the potential environmental relevance of the interaction $O_2(^1\Delta_g)$ -ND. For this reason the k_r values of the model compound 2-amino-4-hydroxy-6-methyl-1,3-pyrimidine (AHMPD) and of some related pyrimidines have been also determined (Table 3) (Pajares et al., 1998, 2000).

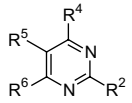
The changes in the absorption spectra during the visible-light irradiation in the presence of RB of air-equilibrated individual solutions of AHMPD in pH 11 aqueous solution are shown in Fig. 5 (Pajares et al., 2000). Similar changes were observed in the mixture MeCN/water 4:1. Under comparative conditions, the spectral modification was much higher in the presence of alkali, but unobservable in the absence of oxygen or in the presence of 10 mM NaN_3 . Experiments on oxygen consumption and time-resolved phosphorescence detection of $O_2(^1\Delta_g)$ demonstrated the involvement of $O_2(^1\Delta_g)$ in the photooxidation. Besides, the evolution with time of the number of NH_2 groups indicated a continuous generation of this group (Fig. 6). The higher values obtained for the rate constants k_t and k_r in alkaline media, where the electron-releasing ability of the OH-group is enhanced by ionization, can be explained by the above cited photooxidation mechanism through a charge-transfer complex (Scheme 4).

The k_r values found for AHMPD indicates that the reactive quenching component is more important in pure water—either in the absence or in the presence of alkali—than in the mixture MeCN/water, as expected. In other words, the proportion of $O_2(^1\Delta_g)$ -quenching events resulting in AHMPD photodegradation increases with the solvent polarity.

Total absence of reactivity was observed in the simpler compounds PD, MPD, APD, and HPD (Table 3) (Pajares et al., 1998, 2000). In the particular case of

Table 3

Rate constants ($M^{-1} s^{-1}$) of overall (k_t) and reactive (k_r) quenching of the $O_2(^1\Delta_g)$ -mediated photooxidation of pyrimidines (PD) in several solvents

Compound					Solvent	$k_t/10^7$	$k_r/10^7$ ^a	k_r/k_t
	R ²	R ⁴	R ⁵	R ⁶				
PD	H	H	H	H	Benzene	<0.001	NQ	~0
APD	NH ₂	H	H	H	D ₂ O	<0.001	NQ	~0
HPD	H	OH	H	H	D ₂ O, pD 6	<0.001	NQ	~0
					D ₂ O, pD 11	<0.001	NQ	~0
MPD	H	H	H	Me	D ₂ O	<0.001	NQ	~0
					D ₂ O, pD 11	<0.001	NQ	~0
AHPD	NH ₂	OH	H	H	Water, pD/pH 6	<0.001	NQ	~0
					Water, pD/pH 11	1.7	1.7	1.00
AHMPD	NH ₂	OH	H	Me	Water, pD/pH 6	0.057	0.018	0.31
					water, pD/pH 11	2.7	1.8	0.66
					MeCN/water 4:1	0.025	0.009	0.36
					MeCN/water 4:1 + KOH	1.46	0.38	0.26
DEAHMPD ^b	NEt ₂	OH	H	Me	CHCl ₃	0.07	NQ	~0
DMAHMPD ^c	NMe ₂	OH	Me	Me	CHCl ₃	1.15	nd	
					H ₂ O, pH 7	8.07	NQ	~0
					H ₂ O, pH 9	14.1	NQ	~0

Data mainly taken from Pajares et al. (1998, 2000).

^a NQ: no reaction was observed; nd: not determined.

^b From Harkness and Wells (1981).

^c From Dixon and Wells (1983).

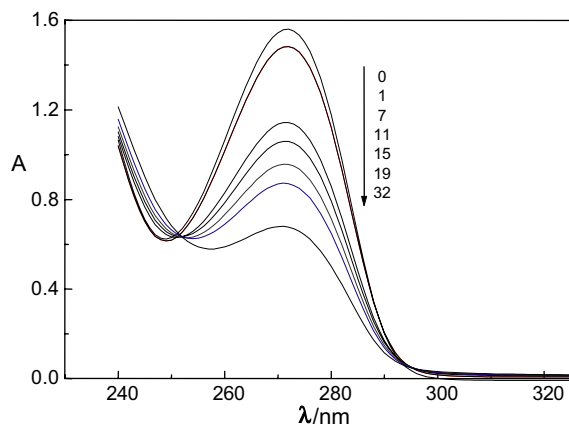


Fig. 5. Spectral evolution during the Rose Bengal-sensitized photooxidation of 2-amino-4-hydroxy-6-methylpyridimidine (AHMPD) in pH 11 aqueous solution. Numbers on the spectra represent irradiation times in min. Adapted from Pajares et al. (2000).

HPD, its lack of reactivity, even in the presence of alkali, seems not in accord with the expected effect of an OH-group—as such or in ionized form—on the kinetics of PD's photooxidations. This indicates that the OH-group in a pyrimidine molecule constitutes a necessary, but not

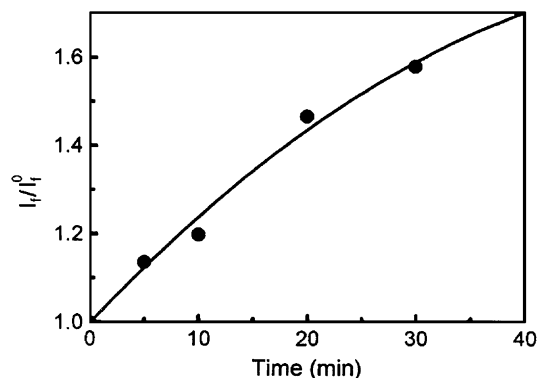
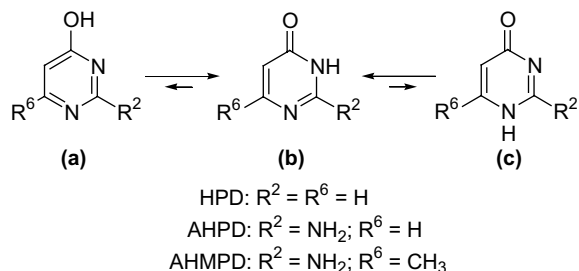


Fig. 6. Temporal evolution of the relative fluorescence intensity in the Rose Bengal-sensitized photooxidation of 2-amino-4-hydroxy-6-methylpyridimidine (AHMPD) in pH 11 aqueous solution after addition of fluorescamine. I_t^0 and I_t are the fluorescence intensities at irradiation times $t=0$ and $t=t$, respectively. Adapted from Pajares et al. (2000).

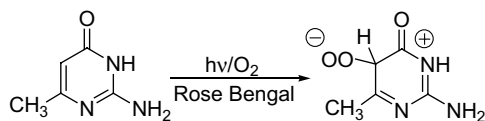
a sufficient, condition for the interaction with $O_2(^1\Delta_g)$. The lack of reactivity of HPD is a consequence of the predominant, or exclusive, presence in water solution of the corresponding tautomeric 4-oxo forms (b) (major) and (c) (minor) (Scheme 9) (Elguero et al., 1976; Boulton and McKillop, 1984; Brown et al., 1994), much less



Scheme 9. Possible tautomeric forms in 4-hydroxypyrimidines HPD, AHPD, and AHMPD.

aromatic than the 4-hydroxy form (a) and, hence, much less reactive towards $O_2(^1\Delta_g)$ (Wilkinson et al., 1995). A similar equilibrium can be envisaged in the case of AHMPD, because in the related compound AHPD the 2-amino-4-oxo forms (b) and (c) coexist in aqueous solution (Elguero et al., 1976), and possible zwitterionic structures have been disregarded. In the presence of alkali, the OH-ionized form of structure (a) predominates, and the reaction with $O_2(^1\Delta_g)$ is favored, as the experimental evidence demonstrates for the case of AHPD, where a total absence of reactivity was observed in pH/pD 6 media. The pH effect on the reactive rate constant k_r is qualitatively similar to that observed for simple substituted phenols (see above), although AHMPD is moderately reactive even under conditions in which the OH-group is not ionized, because the presence of both the 2-amino and, specially, 6-methyl groups increases the electron donor ability of the substrate and, consequently, favors the generation of the encounter complex postulated in Scheme 4. A k_r/k_t value of 0.66 was described for AHMPD in alkaline aqueous solution.

Some information about the oxidative pathway in the sensitized photooxidation of AHMPD can be extracted from the analysis of the evolution of the primary amino groups (Fig. 6), and from the 1:1 stoichiometry found for the reaction between AHMPD and $O_2(^1\Delta_g)$ (Pajares et al., 2000). The stoichiometry is in agreement with the primary generation of a zwitterionic intermediate such as that shown in Scheme 10, also proposed for the sensitized photooxidation of the 2-diethylamino analog DEAHMPD (Dixon and Wells, 1983) (Table 3). Nevertheless, the fluorimetric analysis by fluorescamine complexation of primary amino groups (Straight and



Scheme 10. Possible primary photoreaction in the Rose Bengal-sensitized photooxidation of AHMPD.

Spikes, 1978) during the photooxidation of AHMPD showed the generation of at least one additional NH_2 -group, pointing to the cleavage of the ring, possibly in a further reaction step. The fluorescamine assay is frequently employed as a kinetic and mechanistic tool for the evaluation of the generation or disappearance of primary amino groups upon sensitized photooxidation of different substrates (Pajares et al., 2000; Posadaz et al., 2004).

4. Photooxidations sensitized by riboflavin

The dye Rf is usually present in natural waters (Benassi et al., 1967; Chacon et al., 1988), and surely plays an important role in the natural photodegradation of dissolved contaminants. For these reasons the Rf-sensitized photooxidation, in water or in water–organic solvent mixtures, of the hydroxypyridines 3-HP (Pajares et al., 1999) and 4-HP (Pajares et al., 2001), the hydroxyquinolines 4-HQ and 8-HQ (Criado et al., 2003), and the hydroxypyrimidine AHMPD (Haggi et al., 2002), selected model compounds of some OR–ND pesticides, has been studied. The observed spectral changes during the irradiations indicate the existence of chemical reactions involving both OH–NDs and Rf. Representative changes are shown in Figs. 7 and 8. These changes, and the results from oxygen uptake experiments in the absence and in the presence of NaN_3 —specific quencher of $O_2(^1\Delta_g)$ —or superoxide dismutase (SOD)—specific quencher of $O_2^{\cdot-}$, denote photoprocesses with participation of reactive oxygen species generated by excited triplet Rf. The elucidation of the involved mechanism, as well as the determination of the relative efficiency of the photodegradation process, were performed on the basis of the previous knowledge of the $O_2(^1\Delta_g)$ -mediated process—selectively studied through the above

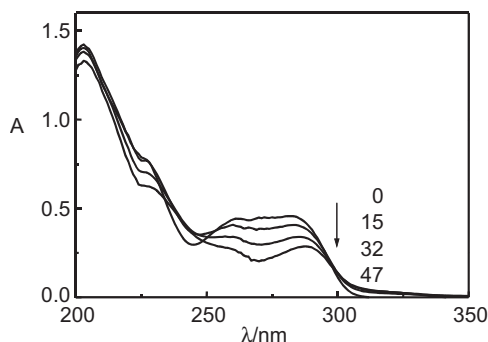


Fig. 7. Spectral changes in the photooxidation of 2-amino-4-hydroxy-6-methylpyrimidine (AHMPD) (0.5 M) sensitized with riboflavin (0.02 mM) in pH 6 aqueous solution. Numbers on the spectra are irradiation times in minutes. Adapted from Haggi et al. (2002).

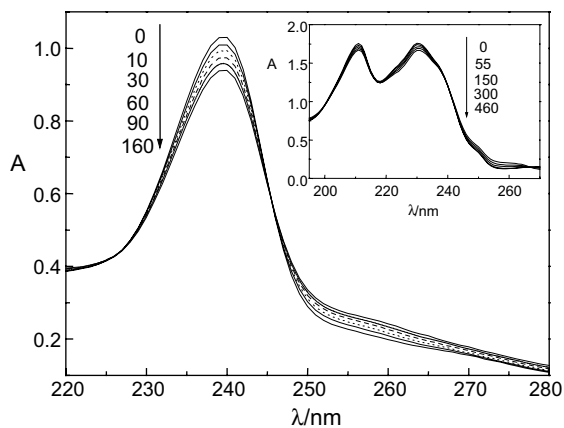


Fig. 8. Spectral evolution during the riboflavin-sensitized photooxidation of 8-hydroxyquinoline (8-OHQ) (main figure) and 4-hydroxyquinoline (4-OHQ) (inset), both 0.03 mM in H₂O/MeOH 9:1 v/v. Numbers on the spectra represent irradiation times in seconds. Adapted from Criado et al. (2003).

RB-sensitized experiments, and by using fluorescence and laser flash photolysis techniques. The presence of the species Rf⁻, a precursor in the generation of O₂⁻, was confirmed by registering the corresponding transient-absorption spectrum (see Fig. 9 for a typical case). In the next sections, the behavior of the cited OH-ND compounds under Rf-sensitized photooxidation conditions is discussed.

4.1. Hydroxypyridines

The visible-light irradiation of the mixture 3-HP plus Rf in air-equilibrated aqueous solution triggers competitive physical and chemical processes that depend on the relative concentration of 3-HP and Rf with regard to that of the dissolved ground state molecular oxygen (0.26 mM in air-equilibrated water solution, according to Murov, 1973). The rate constant values found for the quenching by 3-OHP of O₂(¹Δ_g), excited singlet Rf (¹Rf*), and excited triplet Rf (³Rf*), are shown in Table 4 (Pajares

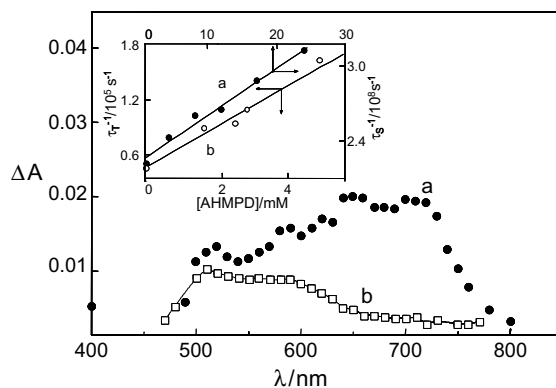


Fig. 9. Transient absorption spectra of riboflavin (0.01 mM) in argon-saturated aqueous solution, in the absence (a) and in the presence (b) of 2-amino-4-hydroxy-6-methylpyrimidine (AHMPD) (8 mM) taken at 1 and 20 μs after the laser pulse, respectively. Spectrum (b) is coincident with the absorption spectrum of riboflavin anion radical. Inset: Stern-Volmer plots for the quenching of ¹Rf* (air-equilibrated solution) (a), and ³Rf* (argon-saturated solution) (b) by AHMPD. Adapted from Haggi et al. (2002).

et al., 1999). According to these values, in the irradiations of solutions with Rf concentration ca. 0.01 mM and 3-HP concentration ≤ 0.01 mM, the predominant pathway is the generation of O₂(¹Δ_g) (process (8), Scheme 3) and the concomitant photooxygenation of 3-HP (process (14)). Under similar conditions, but with 3-HP concentration ca. 0.10 mM, competitive reactions of ³Rf* with both O₂(³Σ_g⁻) (process (8)) and 3-HP (process (9)) are operative, giving rise to: (a) the inhibition of the Rf photodegradation (process (6)); (b) the generation of both O₂(¹Δ_g) and O₂⁻ in a similar extent; and (c) the subsequent photooxygenation of both 3-HP (processes (14) and (16)) and Rf (process (13)). With much higher 3-HP concentrations (≥ 1 mM), the quenching of ¹Rf* (process (3)) predominates, and the photodegradation of Rf is thus prevented. Although an electron transfer mechanism between ¹Rf* and 3-HP could also be operative, consumption of any of these two compounds was

Table 4

Rate constant values (M⁻¹ s⁻¹) for the overall (k_t) and reactive (k_r) quenching of O₂(¹Δ_g) (from Rose Bengal sensitization) by 3-hydroxypyridine (3-HP) and 4-hydroxypyridine (4-HP), and for the quenching of excited singlet (¹k_{qHP}) and triplet (³k_{qHP}) riboflavin by the same compounds, in water solution

Quencher	O ₂ (¹ Δ _g) quenching		Excited-Rf quenching	
	k _t /10 ⁹ ^a	k _r /10 ⁹	¹ k _{qHP} /10 ⁹ ^b	³ k _{qHP} /10 ⁹
3-HP	0.03	0.026	5.9 (5.9)	0.89
4-HP	NQ ^c	–	2.4 (2.7)	0.012

Data taken from Pajares et al. (2001).

^a k_t was determined in D₂O solution.

^b Determined by the single-photon-counting technique or (between brackets) steady-state fluorescence.

^c No quenching was observed.

Table 5

Rate constants ($M^{-1} s^{-1}$) for the quenching of excited singlet ($^1k_{qHQ}$) and triplet ($^3k_{qHQ}$) riboflavin, and relative rates of O_2 -uptake and HQ disappearance in the riboflavin-sensitized photooxidation of 4-hydroxyquinoline (4-HQ) and 8-hydroxyquinoline (8-HQ) in $H_2O/MeOH$ 9:1 v/v

Compound	$^1k_{qHQ}/10^9$	$^3k_{qHQ}/10^9$	O_2 -uptake relative rate	HQ-disapp. relative rate
4-HQ	2.7	0.43	0.19	0.20
8-HQ	2.9	1.60	1	1

Data taken from Criado et al. (2003).

not observed under these conditions, suggesting the prevalence of a back electron transfer process.

The case of the isomer 4-HP is different (Pajares et al., 2001), because this pyridine does not react with $O_2(^1\Delta_g)$ generated by RB sensitization (Table 1). With Rf as a sensitizer, the results indicate that 4-HP quenches both $^1Rf^*$ and $^3Rf^*$, but with rate constants values $^1k_{qHP}$ and $^3k_{qHP}$ differing in two orders of magnitude (Table 4). The photodecomposition of Rf, a known process taking place from $^3Rf^*$, was found to depend on the 4-HP concentration: at ≥ 20 mM limited photodecomposition occurs due to the quenching of $^1Rf^*$, while at ca. 5 mM $^3Rf^*$ is photogenerated and subsequently quenched either by oxygen, giving rise to $O_2(^1\Delta_g)$ (process (8)), or by 4-HP, yielding Rf^- (process (9)). Superoxide dismutase inhibition of the oxygen uptake and flash photolysis experiments indicated that Rf^- yields O_2^- (process (10)) by reaction with the dissolved oxygen, yielding at the same time neutral, ground state Rf. As a global result, both 4-HP and Rf are photodegraded, likely with O_2^- . 4-HP disappears by oxygenation, and no decomposition was observed in the absence of oxygen. On the contrary, Rf photodegradation is favored in the absence of oxygen, because Rf regeneration via O_2^- production is precluded.

4.2. Hydroxyquinolines

The photodegradation of 8-HQ in the presence of Rf is about five times faster than that of 4-HQ under the same conditions, as deduced from results of independent experiments of oxygen uptake and substrate consumption (Table 5) (Criado et al., 2003), suggesting that photooxygenation is the exclusive, or at least the dominant, photodegradation pathway of both HQs. On the other hand, the quenching rate constants of excited-Rf by these HQs indicate that at HQ concentrations < 5 mM the radical anion O_2^- is formed through processes (7) and (10), as well as $O_2(^1\Delta_g)$ through process (8). The global result is that both 4-HQ and 8-HQ are effectively photodecomposed upon aerobic Rf-sensitized irradiation. However, 4-HQ—a compound resistant to $O_2(^1\Delta_g)$ attack—is oxidized through an exclusive O_2^- -mediated mechanism, whereas both $O_2(^1\Delta_g)$ and O_2^- species participate in the photooxidation of 8-HQ. Another important conclusion that can be withdrawn

from these results is that the presence of any HQ protects Rf from its aerobic photodegradation, because the generation of O_2^- by back electron transfer from Rf^- to oxygen (process (10)) regenerates at the same time the pigment Rf.

4.3. Hydroxypyrimidines

The pyrimidine AHMPD is a model compound of the pesticides ethirimol and dimethirimol (see above). As in the above studied cases, the kinetic analysis of the photodegradation of AHMPD in the presence of Rf indicates that a complex scheme of competitive processes operates, all involving $^3Rf^*$ (Haggi et al., 2002). Under sensitizing conditions, i.e. with Rf concentrations ca. 0.02 mM, the photodegradation of the dye and (or) AHMPD depends on the concentration of AHMPD. At AHMPD concentrations ≥ 40 mM, the massive quenching of $^1Rf^*$ (process (3)) dominates ($^1k_{qPD} = 2.7 \times 10^9 M^{-1} s^{-1}$, $^3k_{qPD} = 2.7 \times 10^7 M^{-1} s^{-1}$), preventing in practice the whole photoprocess. At AHMPD concentrations ≤ 5 –10 mM, the formed $^3Rf^*$ (process (4)) reacts either with oxygen or with AHMPD, yielding $O_2(^1\Delta_g)$ (process (8)) and semireduced Rf (Rf^-) (process (9)), respectively. Subsequently, O_2^- can be produced from the reaction of Rf^- with dissolved oxygen (process (10)). As a result, both AHMPD and Rf are photodegraded. AHMPD disappears mainly by oxygenation. As in the cases of the above studied HPs and HPDs, Rf photodegradation is favored in the absence of oxygen because Rf regeneration via O_2^- production is precluded.

5. Conclusions

The experimental evidence indicates that when $O_2(^1\Delta_g)$ is photogenerated under field conditions in aqueous environments—as expected in the presence of $O_2(^1\Delta_g)$ -generating dyes, the $O_2(^1\Delta_g)$ -mediated photooxidation appears as an interesting and, in some cases, very efficient alternative pathway of elimination from the environment of OH-ND pesticides analogs to the herein studied model compounds, in competence with other naturally-occurring processes.

The position of the hydroxy group in OH-ND pesticides plays a key role in the efficiency of their interaction

with $O_2(^1\Delta_g)$. In general, the OH-ionization greatly enhances the photooxidative pathway, and the enhancement depends on the solvent polarity and the medium pH. On the other hand, the exclusive presence of the tautomeric oxo form in the medium suppresses the interaction with $O_2(^1\Delta_g)$. In organic solvents both OH and oxo forms can coexist, while in natural aqueous environments both the pH of the medium and the substituents in the particular OH–ND molecule decide the proportion of these forms. If programmed oxidative photodegradations of OH–ND pesticides are considered, and ruling out the use of direct photoreactions using UV-light with this purpose, a simple change of the medium pH value could allow the switch between reactive and non-reactive $O_2(^1\Delta_g)$ -mediated processes.

Solvent effect on the photooxidation kinetics suggest the participation of a charge-transfer mechanism involving an initial encounter excited complex between $O_2(^1\Delta_g)$ and the OH–ND compound.

The presence of the natural dye-sensitizer Rf—instead of exclusive $O_2(^1\Delta_g)$ -generators—triggers a more complex picture of competitive reactions which are highly dependent on the OH–ND concentration. These reactions include oxygenated and non-oxygenated radical species and eventually produce chemical transformations in both Rf and the OH–ND compound. In a general sense, the results obtained under sensitization with Rf suggest that OH–ND contaminants are susceptible to spontaneous photodegradation under usual environmental conditions through mechanisms mediated by the species O_2^- and $O_2(^1\Delta_g)$. Since practically no OH–ND reaction could be observed under anaerobic conditions, the fate of the radical species ND^+ (process (9)) seems to be the abstraction of an electron from the medium giving rise to the recovery of neutral ND.

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References

Alseberg, T., Balk, L., Nylund, K., de Wit, C., Bignert, A., Olson, M., Odsjö, T., 1994. Persistent Organic Pollutants

and the Environment. AB Fälth's Tryckeri, Värnamo, p. 125.

Amarasekara, A.S., 1999. A new synthesis of quinoline-5,8-quinone. *Synth. Commun.* 29, 3063–3066.

Amat-Guerri, F., López-González, M.M.C., Martínez-Utrilla, R., Sastre, R., 1990. Singlet oxygen photogeneration by ionized and un-ionized derivatives of Rose Bengal and Eosin Y in diluted solutions. *J. Photochem. Photobiol. A: Chem.* 53, 199–210.

Amat-Guerri, F., Pajares, A., Gianotti, J., Stettler, G., Bertolotti, S., Miskoski, S., García, N.A., 1999. Singlet molecular oxygen-mediated photooxidation of 2-substituted 3-hydroxypyridines. *J. Photochem. Photobiol. A: Chem.* 126, 59–64.

Barboiu, M., Guran, C., Jitaru, I., Cimpoesu, M., Supuran, C.T., 1996. Complexes with biologically active ligands. Part 7. Synthesis and fungitoxic activity of metal complexes containing 1,3,5-tris(8-hydroxyquinolino)trichlorocyclotriphosphazatriene. *Met.-Based Drugs* 3, 233–240.

Benassi, C.A., Scoffone, E., Galianzo, G., Jori, G., 1967. Proflavin-sensitized photooxidation of tryptophan and related peptides. *Photochem. Photobiol.* 28, 857–862.

Bertolotti, S.G., Previtali, C.M., Rufs, A.M., Encinas, M.V., 1999. Riboflavin/triethanolamine as photoinitiator system of vinyl polymerization. A mechanistic study by laser flash photolysis. *Macromolecules* 32, 2920–2924.

Bocco, G., Luiz, M., Gutiérrez, M.I., García, N.A., 1994. Influence of the nuclear substitution on the sensitized photooxidation of model compounds for phenolic-type pesticides. *J. Prakt. Chem.* 336, 243–246.

Boulton, A.J., McKillop, A., 1984. Structure of six-membered rings. In: Katrizky, A.R., Rees, C.W. (Eds.), *Comprehensive Heterocyclic Chemistry*, vol. 2. Pergamon Press, Oxford, pp. 1–98.

Brown, D.J., Evans, R.F., Cowden, W.B., Fenn, M.D., 1994. The pyrimidines. In: Taylor, E.C. (Ed.), *The Chemistry of Heterocyclic Compounds*, vol. 52. John Wiley and Sons, New York.

Burrows, H.D., Canle, L.M., Santaballa, J.A., Steenken, S., 2002. Reaction pathways and mechanisms of photodegradation of pesticides. *J. Photochem. Photobiol. B: Biol.* 67, 71–108.

Carlsson, D.J., Suprunchuk, T., Wiles, D.M., 1974. The quenching of singlet oxygen ($^1\Delta_g$) by transition metal chelates. *Can. J. Chem.* 52, 3728–3737.

Chacon, J.N., Mc Learie, J., Sinclair, R.S., 1988. Singlet oxygen yields and radical contributions in the dye-sensitized photooxidation in methanol of esters of polyunsaturated fatty acids (oleic, linoleic, linolenic and arachidonic). *Photochem. Photobiol.* 47, 647–656.

Cossy, J., Belotti, D., 2001. Efficient synthesis of substituted quinoline-5,8-quinones from 8-hydroxyquinolines by photooxygenation. *Tetrahedron Lett.* 42, 4329–4331.

Criado, S., Pajares, A., Gianotti, J., Stettler, G., Escalada, J.P., Bertolotti, S., Amat-Guerri, F., García, N.A., 2003. Kinetic study of the riboflavin-sensitized photooxygenation of two hydroxyquinolines of biological interest. *J. Photochem. Photobiol. B: Biol.* 71, 19–25.

Dalle, J.P., Magous, R., Mousseron-Cannet, M., 1972. Inhibition of l'oxygene singulet. *Photochem. Photobiol.* 15, 411–419.

- Dixon, S.R., Wells, C.H.J., 1983. Dye sensitized photooxidation of 2-dimethylamino-5,6-dimethylpyrimidin-4-ol in aqueous solution. *Pestic. Sci.* 14, 444–448.
- Elguero, J., Marzin, C., Katritzky, A.R., Linda, P., 1976. In: Katritzky, A.R., Boulton, A.J. (Eds.), *The Tautomerism of Heterocycles*. Academic Press, New York (Adv. Heterocycl. Chem. (Suppl. 1)).
- Faizi, S., Siddiqui, B.S., Saleem, R., Akhtar, F., Khan, K.A., Khan, S.A., Siddiqui, S., Parvez, M., Choudhary, M.I., 1997. Mannich reaction product of quinolin-8-ol (oxine) and its antibacterial activity. *Aust. J. Chem.* 50, 861–864.
- Foote, C.S., 1984. Mechanisms of photooxygenation. In: Liss, A.R. (Ed.), *Porphyrin Localization and Treatment of Tumors*. New York, pp. 3–18.
- García, N.A., 1994. Singlet molecular oxygen-mediated photodegradation of aquatic phenolic pollutants. A kinetic and mechanistic overview. *J. Photochem. Photobiol. B: Biol.* 22, 185–196.
- García, N.A., Amat-Guerri, F., 2001. In: Humeres, E., Yunes, R. (Eds.), *Sensitized Photooxidation of Monohydroxylated N-heteroaromatic Compounds*. Florianópolis, Brazil, pp. 198–217.
- Grachev, V.T., Saltzev, B.E., Dyumaev, K.M., Smirnov, L.D., Avezov, M.R., 1973. Structure of 2,3 and 2,5 dihydroxypyridines. *Khim. Getoer. Soedl.* 1, 60–63.
- Gsponer, H.E., Previtali, C.M., García, N.A., 1987. Evidence for physical quenching of singlet oxygen by dinitrophenols. *J. Photochem.* 36, 247–253.
- Haggi, E., Bertolotti, S., Miskoski, S., Amat-Guerri, F., García, N.A., 2002. Environmental photodegradation of pyrimidine fungicides. Kinetics of the visible-light-promoted interactions between riboflavin and 2-amino-4-hydroxy-6-methylpyrimidine. *Can. J. Chem.* 80, 62–67.
- Harkness, G.J., Wells, C.H.J., 1981. Rates of reaction of singlet oxygen with some systemic pyrimidine fungicides and related compounds. *Pestic. Sci.* 12, 215–218.
- Heelis, P.F., Parsons, B., Phillips, G.O., McKellar, J.F., 1981. One-electron oxidation of flavins. A flash photolysis and pulse radiolysis study. *Photochem. Photobiol.* 33, 7–12.
- Johson, C.D., 1984. Pyridines and their benzo derivatives. In: Katritzky, A.R., Rees, C.W. (Eds.), *Comprehensive Heterocyclic Chemistry*, vol. 2. Pergamon Press, Oxford, pp. 99–164.
- Kayirere, M.-G., Mahamoud, A., Chevalier, J., Soyfer, J.-C., Cremieux, A., Barbe, J., 1998. Synthesis and antibacterial activity of new 4-alkoxy, 4-aminoalkyl and 4-alkylthioquinoline derivatives. *Eur. J. Med. Chem.* 33, 55–63.
- Krishna, C.M., Uppuluri, S., Riesz, P., Zigler, J.S., Balasubramanian, D., 1991. A study on the photolysis efficiencies of some lens constituents. *Photochem. Photobiol.* 54, 51–58.
- Larson, R.A., Marley, K.A., 1984. Quenching of singlet oxygen by alkaloids and related nitrogen heterocycles. *Phytochemistry* 23, 2351–2354.
- Luiz, M., Gutiérrez, M.I., Bocco, G., García, N.A., 1993. Solvent effect on the reactivity of monosubstituted phenols towards singlet molecular oxygen ($O_2(^1\Delta_g)$) in alkaline media. *Can. J. Chem.* 71, 1247–1252.
- Lu, C., Lin, W., Wang, W., Han, Z., Yao, S., Lin, N., 2000. Riboflavin (Vitamin B₂) photosensitized oxidation of 2'-deoxyguanosine-5'-monophosphate (dGMP) in aqueous solution: a transient intermediates study. *Phys. Chem. Chem. Phys.* 2, 329–334.
- Lu, C., Bucher, G., Sander, W., 2004. Photoinduced interactions between oxidized and reduced lipoic acid and riboflavin (vitamin B₂). *Chem. Phys. Chem.* 5, 47–56.
- Mártire, D.O., Braslavsky, S.E., García, N.A., 1991. Sensitized photo-oxidation of dihydroxybenzenes and chlorinated derivatives. A kinetic study. *J. Photochem. Photobiol. A: Chem.* 61, 113–124.
- Mártire, D., Evans, Ch., Bertolotti, S., Braslavsky, S.E., García, N.A., 1993. A kinetic study of the singlet molecular oxygen quenching by hydroxybiphenyls. *Chemosphere* 26, 1691–1701.
- Murov, S.L., 1973. *Handbook of Photochemistry*. Marcel Dekker, New York, p. 89.
- Murugasu-Oei, B., Dick, T., 2001. In vitro activity of the chelating agents nitroxoline and oxine against *Mycobacterium bovis* BCG. *Int. J. Antimicrob. Ag.* 18, 579–582.
- Neckers, D.C., 1989. Rose Bengal. *J. Photochem. Photobiol. A: Chem.* 47, 1–29.
- Nicoletti, G., Domalewska, E., Borland, R., 1999a. Fungitoxicity of oxine and copper oxinate: activity spectrum, development of resistance and synergy. *Mycol. Res.* 103, 1073–1084.
- Nicoletti, G., Domalewska, E., Borland, R., 1999b. Fungitoxicity of oxine and copper oxinate: effects of pH, metals and chelating agents on activity. *Mycol. Res.* 103, 1085–1097.
- Okanioto, K.Y., Hondo, F., Hayamad, A., Kusabayashi, S., 1982. Kinetics of dye-sensitized photodegradation of aqueous phenol. *J. Chem. Eng. Jpn.* 15, 368–375.
- Pajares, A., Gianotti, J., Haggi, E., Stettler, G., Amat-Guerri, F., Criado, S., Miskoski, S., García, N.A., 1998. Kinetic study of the singlet molecular oxygen-mediated photodegradation of monohydroxylated N-heteroaromatic compounds. *J. Photochem. Photobiol. A: Chem.* 119, 9–14.
- Pajares, A., Gianotti, J., Haggi, E., Stettler, G., Amat-Guerri, F., Bertolotti, S., Criado, S., García, N.A., 1999. Visible light-promoted interaction between riboflavin and 3-hydroxypyridine in aqueous solution. *Dyes Pigm.* 41, 233–239.
- Pajares, A., Gianotti, J., Stettler, G., Haggi, E., Miskoski, S., Criado, S., Amat-Guerri, F., García, N.A., 2000. Kinetics of the dye sensitized photooxidation of 2-amino-4-hydroxy-6-methylpyrimidine, a model compound of some fungicides. *J. Photochem. Photobiol. A: Chem.* 135, 207–212.
- Pajares, A., Gianotti, J., Stettler, G., Bertolotti, S., Criado, S., Posadaz, A., Amat-Guerri, F., García, N.A., 2001. Modeling the natural photodegradation of water contaminants. A kinetic study on the light-induced aerobic interactions between riboflavin and 4-hydroxypyridine. *J. Photochem. Photobiol. A: Chem.* 139, 199–204.
- Pajares, A., Gianotti, J., Stettler, G., Escalada, J.P., Bertolotti, S., Miskoski, S., Amat-Guerri, F., García, N.A., 2002. Ionization effects on the sensitized photooxidation of 2,3-dihydroxypyridine and 2,4-dihydroxypyridine: a kinetic study. *J. Photochem. Photobiol. A: Chem.* 153, 101–107.
- Palaniappan, A.N., Bharathi, K., Sekar, K.G., 1998. Kinetics of oxidation of oxine by pyridinium dichromate. *Pol. J. Chem.* 72, 122–126.
- Patel, A.D., Sharma, S.M., Vora, J.J., Joshi, J.D., 1997. Synthesis, characterization and antimicrobial activities of binary and ternary complexes of UO₂ II and ThIV complexes with 5-hydroxymethyl-8-quinolinol and

- 8-formyl-7-hydroxy-4-methyl-2H-1-benzopyran-2-one with aniline. *J. Indian Chem. Soc.* 74, 287–288.
- Posadaz, A., Biasutti, A., Casale, C., Sanz, J., Amat-Guerri, F., García, N.A., 2004. Rose Bengal-sensitized photooxidation of the dipeptides Trp–Phe, Trp–Tyr and Trp–Trp. Kinetics, mechanism and photoproducts. *Photochem. Photobiol.* 80, 132–138.
- Scheibel, L.W., Rodriguez, S., 1989. Antimalarial activity of selected aromatic chelators. V. Localization of iron-59 in *Plasmodium falciparum* in the presence of oxines. *Prog. Clin. Biol. Res.* 313 (Malar. Red Cell), 119–149.
- Shen, A.Y., Chen, C.P., Roffler, S., 1999a. A chelating agent possessing cytotoxicity and antimicrobial activity: 7-Morpholinomethyl-8-hydroxyquinoline. *Life Sci.* 64, 813–825.
- Shen, A.Y., Wu, S.-N., Chiu, C.-T., 1999b. Synthesis and cytotoxicity evaluation of some 8-hydroxyquinoline derivatives. *J. Pharm. Pharmacol.* 51, 543–548.
- Sircar, I., Haleen, S.J., Burke, S.E., Barth, H., 1992. Synthesis and biological activity of 4-(diphenylmethyl)- α -(4-quinolinyl-oxymethyl)-1-piperazineethanol and related compounds. *J. Med. Chem.* 35, 4442–4449.
- Straight, R., Spikes, J.D., 1978. Sensitized photooxidation of amino acid: effects on the reactivity of their primary amino groups with fluorescamine and *o*-phthalaldehyde. *Photochem. Photobiol.* 27, 565–569.
- Thomas, M.J., Foote, C.S., 1978. Chemistry of singlet oxygen XXVI. The photooxygenation of phenols. *Photochem. Photobiol.* 27, 683–693.
- Tomlin, C., 1994. *The Pesticide Manual*. British Crop Protection Council and The Royal Society of Chemistry, London, UK.
- Valli, G., Sivakolunthu, S., Muthusubramanian, S., Sivasubramanian, S., 2000. Synthesis and biological activity of copper(II) mixed ligand complexes with thiophene-2-aldehyde thiosemicarbazone as the primary ligand. *J. Indian Chem. Soc.* 77, 252–253.
- Vo, D., Wolowyk, M.W., Knaus, E.E., 1993. Synthesis and β -adrenergic antagonist activity of heterocyclic propanolamines. *Drug Des. Discovery* 10, 89–99.
- Wilkinson, F., Helman, W.P., Ross, A.B., 1993. Quantum yields for the photosensitized formation of the lowest electronically excited singlet state of molecular oxygen in solution. *J. Phys. Chem. Ref. Data* 22, 133–262.
- Wilkinson, F., Helman, W.P., Ross, A., 1995. Rate constants for the decay of the lowest electronically excited singlet state of molecular oxygen in solution. An expanded and revised compilation. *J. Phys. Chem. Ref. Data* 24, 663–1021.
- Young, R.H., Brewer, D.R., 1976. In: Ranby, B., Rabek, J.F. (Eds.), *Singlet Oxygen Reactions with Organic Compounds and Polymers*. Wiley, New York, pp. 36–43.