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Advanced oxidation treatment and photochemical fate of selected antidepressant pharmaceuticals in solutions of Suwannee River humic acid

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ABSTRACT

Antidepressant pharmaceuticals have recently been detected at low concentrations in wastewater and surface water. This work reports studies of the direct and indirect photochemical fate and treatment by advanced oxidation of three antidepressant compounds (duloxetine, venlafaxine and bupropion) in solutions of humic acid in order to elucidate their behavior in the natural environment prior to reaching a water treatment facility and potentially entering a potable water supply. Humic acid solution was prepared by adding to distilled water a known amount of organic matter as a photosensitizer. All three antidepressants react very rapidly with hydroxyl radicals (•OH) and hydrated electrons (e^-_{aq}) with rate constants of ~10^8 to 10^{10} M^{-1} s^{-1}, but significantly slower with singlet oxygen ($^1\Delta O_2$) (~10^3 to 10^5 M^{-1} s^{-1}). The steady-state concentrations of •OH and $^1\Delta O_2$, in a sample of humic acid solution were measured and used with the second order rate constants to show that the hydroxyl radical was an order of magnitude more effective than the singlet oxygen in the solar-induced photochemical degradation of the antidepressants. Excited state dissolved organic matter also accounted for a substantial portion of degradation of duloxetine, decreasing its half-life by 27% under solar irradiation. Several reaction pathways and by-products arising from the photodegradation were identified using gamma-irradiation followed by LC–MS analysis.

1. Introduction

Pharmaceuticals and personal care products have been recently classified as emerging pollutants of concern, in that they constitute a new class of pollutants that have been detected in the environment but whose effects and fate remain poorly understood [1,2]. Pharmaceuticals are consumed by humans and animals and may be excreted in both unmetabolized and metabolized forms [3] and enter the environment through wastewater, or they may simply be dumped "down the drain" by consumers or medical facilities [4–6]. Once in the environment, they can have unknown, and hence potentially serious consequences to aquatic ecosystems, including toxicity to algae [7] and aquatic organisms [8].

Antidepressants are a class of pharmaceuticals used primarily to treat the symptoms of depression but can also be used to treat a wide variety of other medical conditions including sleep and eating disorders, alcohol and drug abuse, panic, chronic pain and post-traumatic stress disorder [9]. They are commonly prescribed for long-term use, leading to an increased production volume compared to many other types of pharmaceuticals [10]. An estimated 26.2% of Americans ages 18 and older suffer from a diagnosable mental disorder in a given year, including 14.8 million who suffer from major depressive disorder [11], giving rise to a market for branded antidepressants estimated to be worth US$14 billion [12].

Antidepressants can be divided into several classes, according to their structure and mode of action. This paper focuses on two representative compounds, duloxetine and venlafaxine, from the class of serotonin–norepinephrine reuptake inhibitors (SNRIs) which act on the two named neurotransmitters in the brain. SNRIs, due to their higher antidepressant efficacy [13,14], are more widely used than the older selective serotonin reuptake inhibitors (SSRIs) which act on only one neurotransmitter. In addition, one norepinephrine–dopamine reuptake inhibitor, bupropion, which is widely used as both an antidepressant and a smoking cessation aid, was also studied [15]. Duloxetine, venlafaxine and bupropion had sales of $2.6 billion, $1.4 billion and $189 million, respectively, in the United States in 2010 [16].

Several studies have confirmed the presence of these antidepressants in treated wastewater at detectable concentrations. Up to 2.19 $\mu g L^{-1}$ of venlafaxine and 1.9 $ng L^{-1}$ of duloxetine has been reported in secondary-treated effluent of the Metropolitan Wastewater Treatment Plant in St. Paul, Minnesota [17], and

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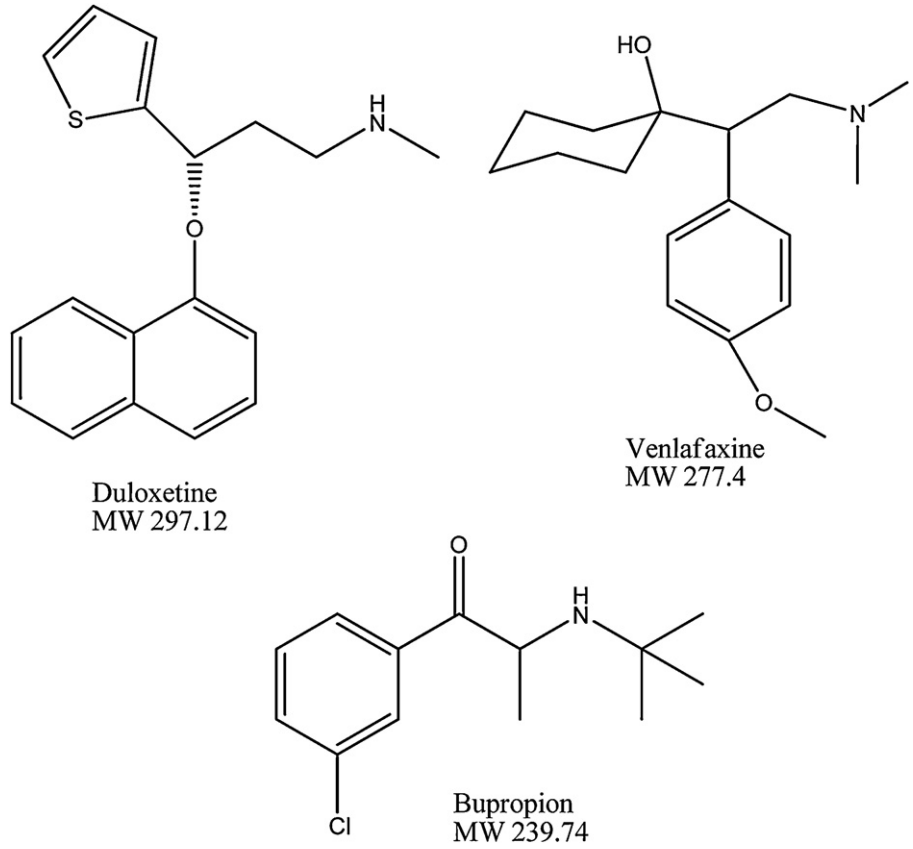


Fig. 1. Chemical structures of antidepressant pharmaceuticals.

venlafaxine was detected at 2.01 $\mu g\,L^{-1}$ in a treated sewage sample from Catalonia, Spain [18]. Duloxetine, bupropion and venlafaxine have also been detected at concentrations of 1.2, 50 and 900 $ng\,L^{-1}$, respectively, at a sampling site 1.7 km downstream from the Pecan Creek treatment plant in Texas [17]. These examples show that these compounds are present in wastewater and are not removed during the treatment process, therefore being discharged into the environment where they are persistent and not immediately degraded as they proceed downstream.

Currently utilized treatment technologies are often not effective in removing pharmaceutical compounds from wastewater [19–21], resulting in their detection in bodies of receiving water where they are exposed to natural sunlight in the presence of organic matter that is ubiquitous in the environment. Photochemical degradation is therefore likely to be an important loss mechanism for many pharmaceutical pollutants in surface waters [2], but photochemistry in natural waters is more complex than in pure water due to the presence of dissolved organic matter (DOM) and other photoactive dissolved and particulate constituents [22]. Dissolved organic matter, when irradiated, produces various reactive species that can react with organic pollutants. This indirect degradation is in addition to the direct degradation caused by the irradiation of the organic pollutants themselves. However, at high concentrations, DOM can interfere with the ability of light to penetrate the water, resulting in a decrease in degradation rates. Since antidepressant pharmaceuticals are not completely removed in wastewater treatment plants, it is important to understand the details of any sunlight-induced degradation that might occur in the environment because many communities obtain their water supply from bodies of water that contain treated wastewater discharged by upstream residents [23].

The purpose of the present research was to perform a preliminary investigation of the degradation of three antidepressants induced by direct and indirect photolysis in humic acid solution, and to measure their absolute bimolecular reaction rate constants with three reactive species: hydroxyl radical (•OH), hydrated electrons (e^-_{aq}) and singlet oxygen ($^1\Delta O_2$). As it turns out, •OH is the most important reactive species in the photodegradation of the antidepressants, and is also the basic reactive species in advanced oxidation. Studies of the degradation products were also performed using gamma-irradiation followed by LC–MS analysis to elucidate the initial stages of the hydroxyl radical-induced degradation mechanisms for these compounds, in order to provide an indication of the species that may be expected to be formed when these compounds degrade in the environment.

2. Methods and materials

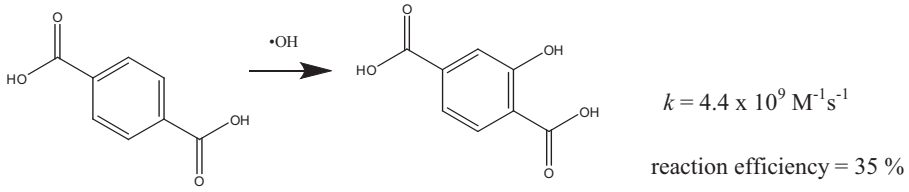
2.1. Chemicals

Duloxetine, venlafaxine, and bupropion (Fig. 1) were obtained from Teva Pharmaceuticals, and confirmed to be greater than 99% purity by HPLC analysis. Humic acid solution was prepared by dissolving 25 $mg\,L^{-1}$ Suwannee River humic acid, SRHA (International Humic Substance Society Catalog No. 2S101H) in deionized water. The SRHA contained 52.63% carbon by weight [24], giving 13 $mg\,L^{-1}$ carbon content. Furfuryl alcohol, furfural (CAS No. 98-01-1), 2-chloroethanol, Rose Bengal and sorbic acid were purchased from Sigma–Aldrich, and isopropanol from EMD Chemicals.

2.2. Photolysis

Direct and indirect photodegradation experiments were performed on aqueous solutions of the three antidepressant compounds in the absence and presence of SRHA, respectively, using a Rayonet RPR-100 photochemical reactor (Southern New

England Ultra Violet Company, Branford, CT) with sixteen 350-nm bulbs arranged vertically around the circumference of the chamber. Each lamp produced high-intensity ($\sim 10^{16}$ photons s^{-1} cm^{-3}) UV light at 350 nm. Radiation was done at room temperature (22 °C) and a rotating tray was used to ensure consistent radiation for all the samples, which had a path length of 1 cm and were approximately 3 cm from the bulbs. Concentrations of the three antidepressants were measured using an Agilent 1200 series HPLC using a UV/vis detector. A Phenomenex Gemini C_{18} column (250 mm × 4.6 mm i.d.) was utilized, and the isocratic mobile phase consisted of various mixtures of methanol and 10 mM phosphate buffer solution in water, depending on the compound to be measured.



$k = 4.4 \times 10^9\ M^{-1}s^{-1}$

reaction efficiency = 35 %

terephthalic acid 2-hydroxy terephthalic acid (2)

2.3. Measurement of reaction rate constants

Electron pulse radiolysis measurements were performed using an 8-MeV Titan Beta model TBS-8/16-1S linear accelerator, which has been described in detail elsewhere [25]. Dosimetry experiments used 2 ns pulses, which generated radical concentrations of 1–3 μM per pulse. For each experiment, 12–15 replicate trials were run, with sample introduction in continuous flow mode, and the results averaged.

When aqueous solutions are irradiated with high-energy radiation, the water absorbs most of the radiation producing a number of reactive species [26] as shown in Eq. (1).

$$H_2O/\backslash/\backslash \rightarrow e^-_{aq} + H^\bullet + {}^\bullet OH + H_2 + H_2O_2 + H_3O^+ \quad (1)$$

To isolate reactions of •OH, sample solutions were saturated with nitrous oxide, which converts solvated electrons and hydrogen atoms to hydroxyl radicals [27]. Similarly, to isolate reactions with e^-_{aq}, solutions were sparged with N_2 and mixed with 0.10 M isopropanol to remove the highly reactive •OH and H• by forming the relatively inert isopropyl radical [27].

Transient, free radical spectra produced by •OH reaction with each pharmaceutical compound were obtained shortly after irradiation in order to help characterize the reaction mechanisms with each radical (Fig. S1).

The bimolecular reaction rate constant of each antidepressant with singlet oxygen was determined by utilizing competition kinetics. These experiments were conducted in a Luzchem solar simulator with a 300 W xenon lamp (Luzchem Research, Inc., Ottawa, ON) set at 2×10^4 lm m^{-2}, which is a typical value for sunlight during daytime. A solution consisting of 0.13 mM of pharmaceutical and 0.18 mM furfural was prepared and 98 μM Rose Bengal was added as a singlet oxygen sensitizer [28]. The mixture was photolyzed in the solar simulator and the degradation of the pharmaceutical and furfural was monitored as a function of irradiation time (t) by HPLC.

2.4. Measurement of reactive species concentrations

The steady state concentration of each reactive species arising from photolysis in the solution of aquatic humic acid was measured in order to determine their relative importance in the degradation process. Using the method of initial rates, the concentration of hydroxyl radical was measured by irradiating the solution in the solar simulator in the presence of 0.60 mM terephthalic acid and monitoring the production of 2-hydroxy terephthalic acid by HPLC (described in Section 2.2), but with a fluorescence detector ($\lambda_{excitation}$ = 315 nm; $\lambda_{emission}$ = 425 nm). The production of the hydroxylated byproduct is shown in Eq. (2).

The rate and reaction efficiency of this reaction are known, enabling the determination of the steady state •OH concentration [29–31].

The presence of hydrated electrons was investigated by irradiating the humic acid solution in the presence of 4.47 mM 2-chloroethanol and monitoring the potential production of chloride ions (Eq. (3)) by ion chromatography [32] using a Dionex DX 120 chromatograph with a mobile phase consisting of 1 mM $NaHCO_3$ and 3.5 mM Na_2CO_3 at a flow rate of 0.75 mL min^{-1} [32]

$$ClCH_2CH_2OH + e^-_{aq} \rightarrow Cl^- + {}^\bullet CH_2CH_2OH, \quad k = 5.6 \times 10^8\ M^{-1}\ s^{-1} \quad (3)$$

The steady state concentration of singlet oxygen in the photolyzed humic acid solution was measured by irradiating the solution in the presence of furfuryl alcohol (initially at 0.16 mM) and monitoring its destruction by HPLC [33]. This reaction is shown in Eq. (4) [34]:

$$FFA + {}^1\Delta O_2 \rightarrow \text{substrate}, \quad k = 1.2 \times 10^8\ M^{-1}\ s^{-1} \quad (4)$$

2.5. Effect of excited state dissolved organic matter

The intermediacy of the triplet excited state dissolved organic matter (^{3}DOM*) was probed by monitoring the degradation of 1 mM duloxetine in humic acid solution in the UV irradiator described in Section 2.2. The experiment was then repeated under four sets of conditions: (1) purging the samples with oxygen, a ^{3}DOM* quencher [35] before and during irradiation, (2) purging with nitrogen before and during irradiation to decrease the oxygen concentration, (3) adding 2,4-hexadienoic acid (sorbic acid) at 1 mM as a ^{3}DOM* quencher [36], and (4) adding isopropanol (1 mM) to quench the hydroxyl radical.

2.6. •OH degradation byproducts and degradation efficiencies

Degradation mechanisms and efficiencies were determined using gamma radiolysis followed by liquid chromatography/mass spectrometry. Gamma radiolysis was performed in a J.L. Shepherd (San Fernando, CA) Mark I Model A68 Irradiator which has a fixed central rod Cesium-137 source calibrated using Fricke dosimetry. The radiation dose varied as a function of time and distance from the radiation source. Samples were saturated with air and irradiated in glass test tubes. The liquid chromatography/mass spectrometry system consisted of an Agilent 1100 HPLC Pump and a Waters LCT Classic Mass Spectrometer with an electrospray ionization source, as described previously [37].

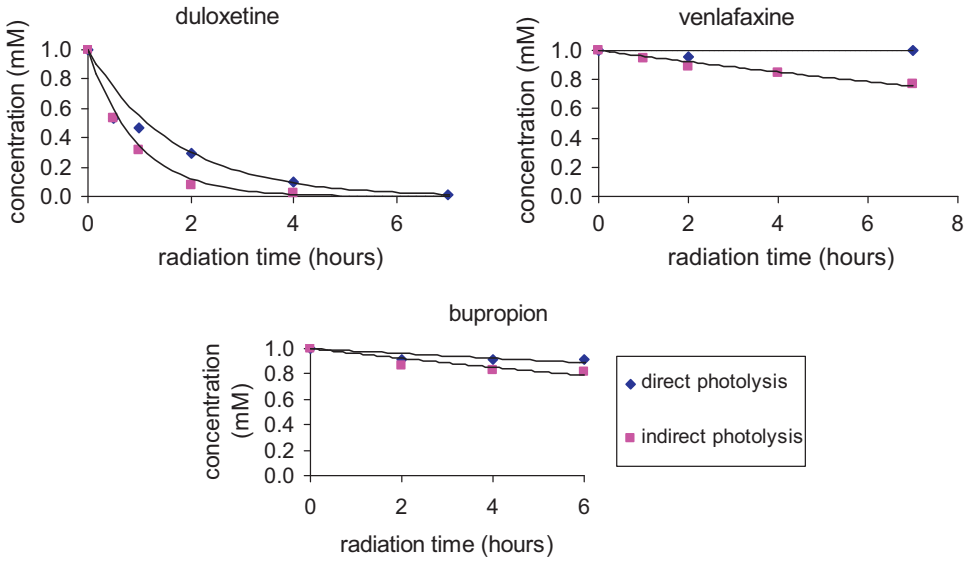


Fig. 2. Direct and indirect photodegradation of antidepressants in sunlight. Indirect photolysis experiments were performed in the presence of 25 mg L^{-1} Suwannee River humic acid.

3. Results and discussion

3.1. Photolysis

The photodegradation of each antidepressant is shown in Fig. 2 as a function of irradiation time, with degradation curves drawn using exponential decay kinetics. The absorption spectra of these compounds are shown in Fig. S2 (Supporting information). Of the three compounds, duloxetine was the most susceptible to direct photolysis, with a half-life of less than an hour. Bupropion degrades at a much slower rate, and venlafaxine does not appear to undergo direct photolysis at all. Despite any possible light screening effects, all three compounds degraded faster in the presence of SRHA, likely due to the additional contribution of indirect photolysis [38]. Upon the addition of SRHA, venlafaxine showed an increase in the rate of degradation, with approximately 25% of the parent compound degraded after 7 h. Bupropion degraded about twice as rapidly in the presence of DOM (18% of parent compound removed after 6 h, compared to 9% in the absence of SRHA), indicating that 50% of its degradation is due to indirect photolysis. The degradation of duloxetine was also accelerated in the presence of the organic matter, although the difference was less notable due to the rapid direct photolysis for this compound. It should be noted that a high concentration of dissolved organic matter, 25 mg L^{-1}, was used to magnify the effect of indirect photolysis, but in many natural bodies of water, the actual DOM concentration is somewhat lower [39]. However, the present results demonstrate that all three antidepressants are likely to degrade in natural waters containing DOM to various extents when exposed to sunlight.

3.2. Reaction rate constants

Absolute bimolecular reaction rate constants for the hydroxyl radical and hydrated electron were calculated from the rate of change of their absorption with concentration at the wavelength of maximum absorption, using the procedure established by Mezyk et al. [40]. This involves fitting exponential functions to growth curves at various concentrations to determine pseudo first-order rate constants and plotting these as a function of concentration. The resulting linear curves indicated second-order reactions. Representative plots are shown in supporting information, Figs. S3 and S4. Bimolecular reaction rate constants for singlet oxygen were determined utilizing competition kinetics, with furfural as the competition agent (Eq. (5)) due to its slow rate of reaction with singlet oxygen [33]. All rate constants are summarized in Table 1, and as absolute rate constants, they are valid regardless of the source of reactive species [41].

$$k_{\text{pharm}} = \frac{\ln([\text{pharm}]_t/[\text{pharm}]_0)}{\ln([\text{furfural}]_t/[\text{furfural}]_0)} k_{\text{furfural}},$$

$$\text{where } k_{\text{furfural}} = 8.4 \times 10^4 \ \text{M}^{-1}\,\text{s}^{-1} \tag{5}$$

Rate constants for all antidepressants with hydroxyl radicals are very rapid, likely due to the presence of highly reactive aromatic rings on all three compounds. Similarly rapid •OH rate constants have been reported for other pharmaceuticals, particularly those with aromatic rings [5,37]. The reaction rate for bupropion is slower than the other two antidepressants by a factor of ~3, possibly because it has a less "bulky" structure and less branching. Duloxetine has a slightly higher reaction rate than venlafaxine, which could be related to the larger number of aromatic rings present. Rate constants for the hydrated electron are also rapid, but those of venlafaxine are slower than the others by two orders of magnitude.

Rate constants for singlet oxygen were calculated as shown by the example in Fig. 3 and were at least four orders of magnitude

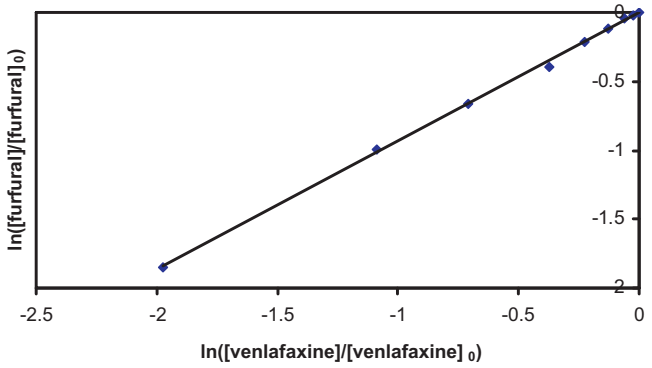


Fig. 3. Degradation of venlafaxine and furfural with Rose Bengal used as a sensitizer. Competition kinetics was used to calculate the rate constant for reaction between venlafaxine and $^1\Delta O_2$.

Table 1
Rate constants for antidepressants with reactive species.

Compound	k (•OH) ($M^{-1}s^{-1}$)	k (e^-_{aq}) ($M^{-1}s^{-1}$)	k ($^1\Delta O_2$) ($M^{-1}s^{-1}$)
Duloxetine	$(9.72 \pm 0.24) \times 10^9$	$(2.15 \pm 0.14) \times 10^{10}$	$(4.89 \pm 0.45) \times 10^4$
Venlafaxine	$(8.15 \pm 0.37) \times 10^9$	$(4.53 \pm 1.18) \times 10^8$	$(9.03 \pm 0.04)) \times 10^4$
Bupropion	$(3.30 \pm 0.15) \times 10^9$	$(2.74 \pm 0.29) \times 10^{10}$	$(7.70 \pm 0.93)) \times 10^3$

lower than those of •OH or e^-_{aq} (see Table 1). These rate constants are on the same order as amoxicillin [42] and four orders of magnitude lower than atorvastatin [43].

3.3. Measurement of reactive species concentrations.

The steady-state concentration of hydroxyl radical in humic acid solution due to solar photolysis was measured based on the oxidation of terephthalic acid, which can be described by Eq. (6).

$$\frac{d[\text{TA}-\text{OH}]}{dt} = k[\text{TA}][^\bullet\text{OH}] \quad (6)$$

The time dependence of the concentration of the hydroxylated byproduct, [TA–OH] is shown in Fig. 4. From the initial data points a steady state [•OH] was calculated as 3.96×10^{-17} M using Eq. (6), a value consistent with those found for natural waters [44–46].

Previous literature [47,48] would suggest that it is unlikely that hydrated electrons could be detected in the humic acid solution exposed to sunlight, and this situation was confirmed in the present study. A sample was irradiated in the presence of 2-chloroethanol at 4.5 mM (Eq. (3)), in the absence of any pharmaceutical, and no chloride ions could be detected by the ion chromatograph, which has a detection limit of 1.99 mg L^{-1}.

The destruction of furfuryl alcohol (FFA) when irradiated in humic acid solution is described by Eq. (7):

$$\frac{d[\text{FFA}]}{dt} = k[\text{FFA}][^1\Delta O_2] \quad (7)$$

Based on the measured initial rate of degradation shown in Fig. 5, the steady state concentration of $^1\Delta O_2$ was calculated to be 5.83×10^{-13} M. This number is on the same order of magnitude as those found in a previous study of humic substances [49] and 1–2 orders of magnitude higher than those found in lake water [46].

The relative importance of each reactive species for the degradation of each pharmaceutical compound is a function of both the bimolecular reaction rate constant and the steady state concentration of the reactive species. This can be quantified by calculating the product of these two values. From these present results, it is apparent that the hydroxyl radical is the most significant reactive species, accounting for the destruction of 13, 6 and 29 times more pharmaceutical molecules than the singlet oxygen, in the cases of duloxetine, venlafaxine and bupropion, respectively. Therefore, measurements of degradation efficiencies and product studies to elucidate the degradation mechanism of each antidepressant were focused on the hydroxyl radical.

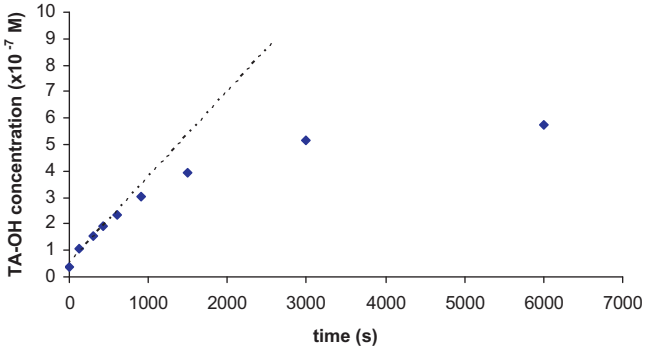


Fig. 4. Formation of hydroxylated byproduct of terephthalic acid, used to calculate steady state concentration of •OH.

3.4. Effect of excited state dissolved organic matter

The photodegradation of duloxetine was monitored under various conditions in order to measure the contribution of ^{3}DOM* to its degradation (Fig. 6). As can be seen, saturating the solution with nitrogen increased the rate of degradation, while the addition of oxygen produced the opposite result. Because oxygen is a ^{3}DOM* quencher [35] and adding nitrogen will remove oxygen, this result suggests that ^{3}DOM* is a significant factor in the degradation of duloxetine. Sorbic acid, another triplet state quencher [50], also reduced the degradation rate for duloxetine. The half life in the presence of 1 mM sorbic acid was 73 min, compared to 53 min without the quencher. The addition of 10 mM isopropanol, an •OH quencher, increased the half life by a negligible amount (<1 min), suggesting that ^{3}DOM* is significantly more important in the degradation of duloxetine than the hydroxyl radical.

3.5. •OH degradation efficiencies

These experiments were performed using ^{137}Cs steady-state radiolysis of air-saturated solutions of the antidepressants and assigning products based on LC–MS measurements. At the low

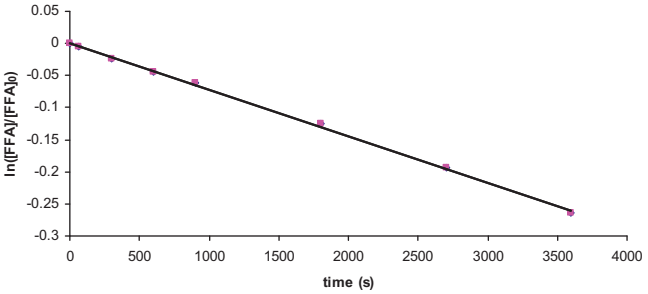


Fig. 5. Degradation of furfuryl alcohol in simulated natural water, used to determine steady state concentration of singlet oxygen.

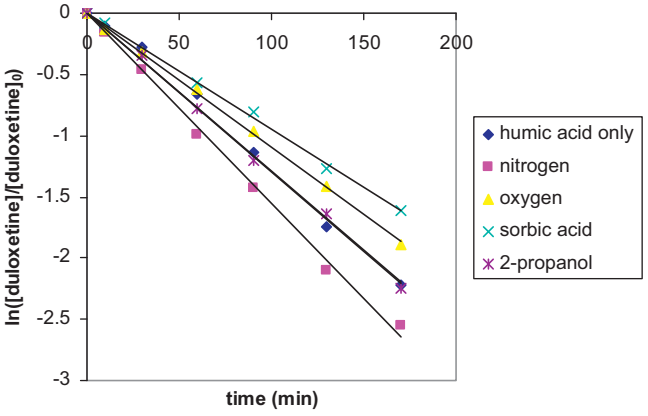


Fig. 6. Photodegradation of duloxetine in the presence of various quenching agents.

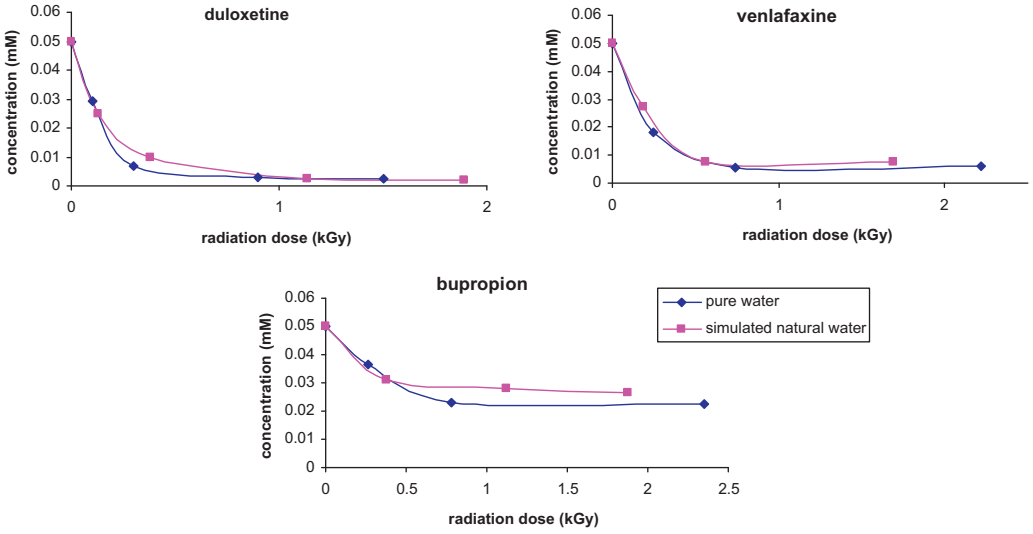


Fig. 7. Degradation of antidepressant solutions by γ-irradiation in pure water and simulated natural water, as monitored by HPLC-UV.

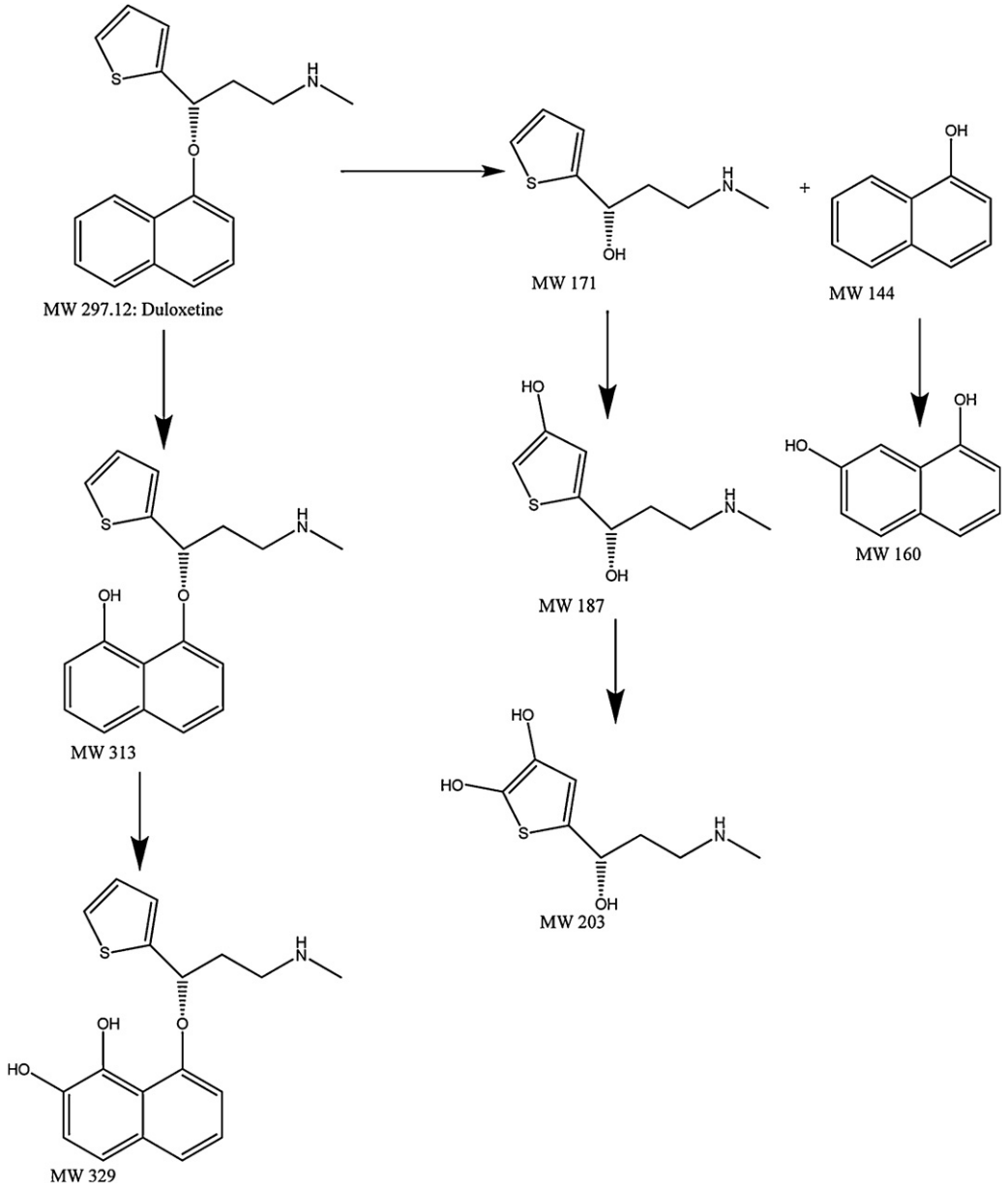


Fig. 8. Hydroxyl radical reaction products for duloxetine.

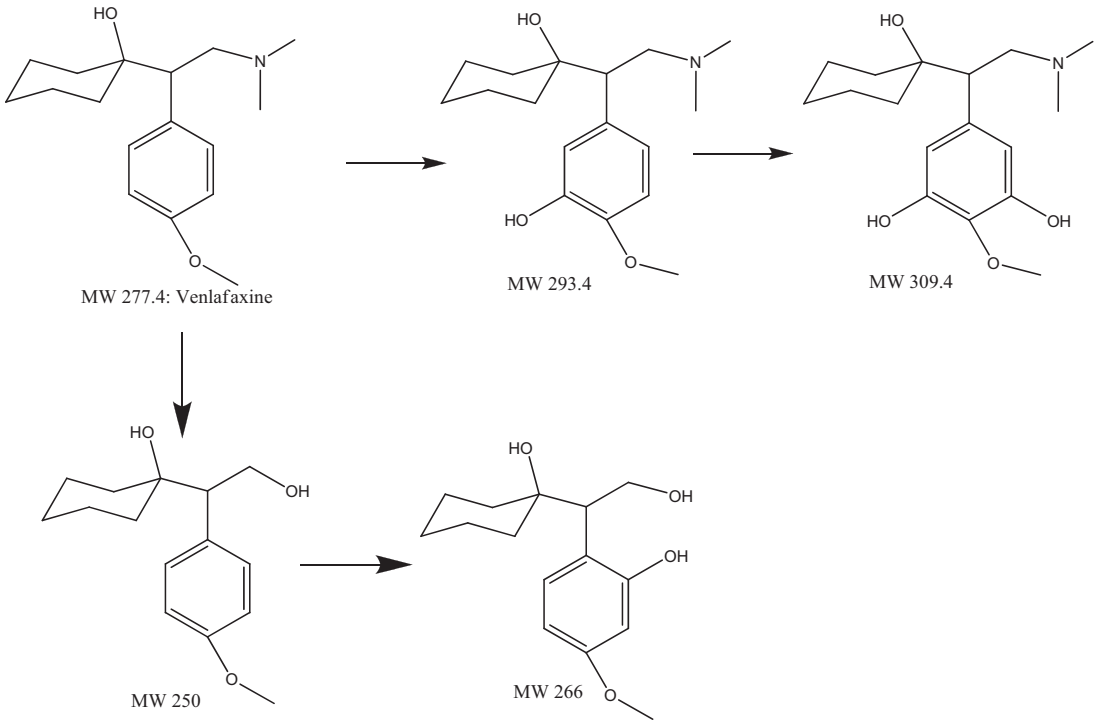


Fig. 9. Hydroxyl radical reaction products for venlafaxine.

radiation doses used in this study, the hydrated electrons and hydrogen atoms produced by the radiolysis in the presence of air are expected to mostly react with dissolved oxygen, to produce the relatively inert superoxide anion [51]. Therefore, under these conditions, the chemistry will be mostly dominated by the •OH reactions. Degradation curves are shown in Fig. 7. Unlike the case of photolysis induced by simulated solar irradiation, all three antidepressants break down rapidly under gamma radiation, with little difference observed upon the addition of DOM to simulate natural water conditions. Degradation efficiencies (Table 2), give the percent of radical reactions resulting in the degradation of a molecule and were calculated as described previously [40]. These values vary widely for the three compounds but do not seem to be affected by the presence of dissolved organic matter, and should be equally valid regardless of the source of •OH.

3.6. •OH degradation byproducts

Degradation mechanisms were determined using gamma radiolysis followed by LC–MS. Since these experiments were performed in air-saturated solutions, hydrated electrons and hydrogen atoms produced in the radiolysis are expected to react with dissolved oxygen to produce the superoxide anion, leaving the hydroxyl radical as the major reactive species. The structures obtained provide a good indication of the compounds which are likely to be formed by the reaction of •OH with the target compounds in the environment. For the purposes of this paper, the products are referred to by molecular weight (MW).

The degradation of duloxetine yielded several products as shown in Fig. 8. The parent molecule has several hydroxylation sites where •OH may attach to a benzene ring, and two such hydroxylation reactions were observed in sequence, yielding products of MW 313 and 329. LC–MS does not permit us to determine at which sites the hyxroxylation occurs. The fragmentation of the molecule at the C—O bond was also observed, resulting in products of MW 171 and 144, and these can undergo hydroxylation, as shown in Fig. 8.

Venlafaxine (Fig. 9) also undergoes sequential hydroxylation yielding products with MW 293, 309 and 325. The peak corresponding to double hydroxylation appears at two distinct retention times, confirming that the reaction can occur at two sites, either independently or simultaneously. The hydroxyl radical may also attack at the nitrogen group, giving MW 250, which can then undergo hydroxylation to give MW 266. Fragmentation of venlafaxine was not observed.

Bupropion (Fig. 10), like the other members of the group, can undergo a series of hydroxylation reactions (MW 255 and 271). A sample spectra is shown in Fig. S5, demonstrating the multiple peaks that arise for MW 255, which indicates that the hydroxyl group can attach to the aromatic ring in multiple locations, each producing a peak at the same molecular weight but at a different retention time. Bupropion's chlorine atom can also be replaced with a hydroxyl group to give MW 221. This reaction is similar to the de-fluorination pathway reported for fluoroquinolones [37] where loss of halogen atoms may be associated with loss of biological activity [52]. This dehalogenated species, MW 221, may then undergo hydroxylation twice (MW 237 and 253). In addition, several fragments of bupropion were detected (MW 144, 145, 170 and 199).

Despite the divergent structures of the members of the antidepressant group, there are common trends in the degradation byproducts. All three molecules readily undergo hydroxylation at several sites, due to the high reactivity of the hydroxyl radical. This mechanism has been reported for other pharmaceuticals, including

Table 2
Reaction efficiencies for reaction of antidepressants with hydroxyl radical in pure and simulated natural water. Simulated natural water contains 25 mg L^{-1} Suwannee River humic acid.

Compound	Pure water	Simulated natural water
Duloxetine	73.7%	71.8%
Venlafaxine	46.3%	43.6%
Bupropion	18.4%	18.1%

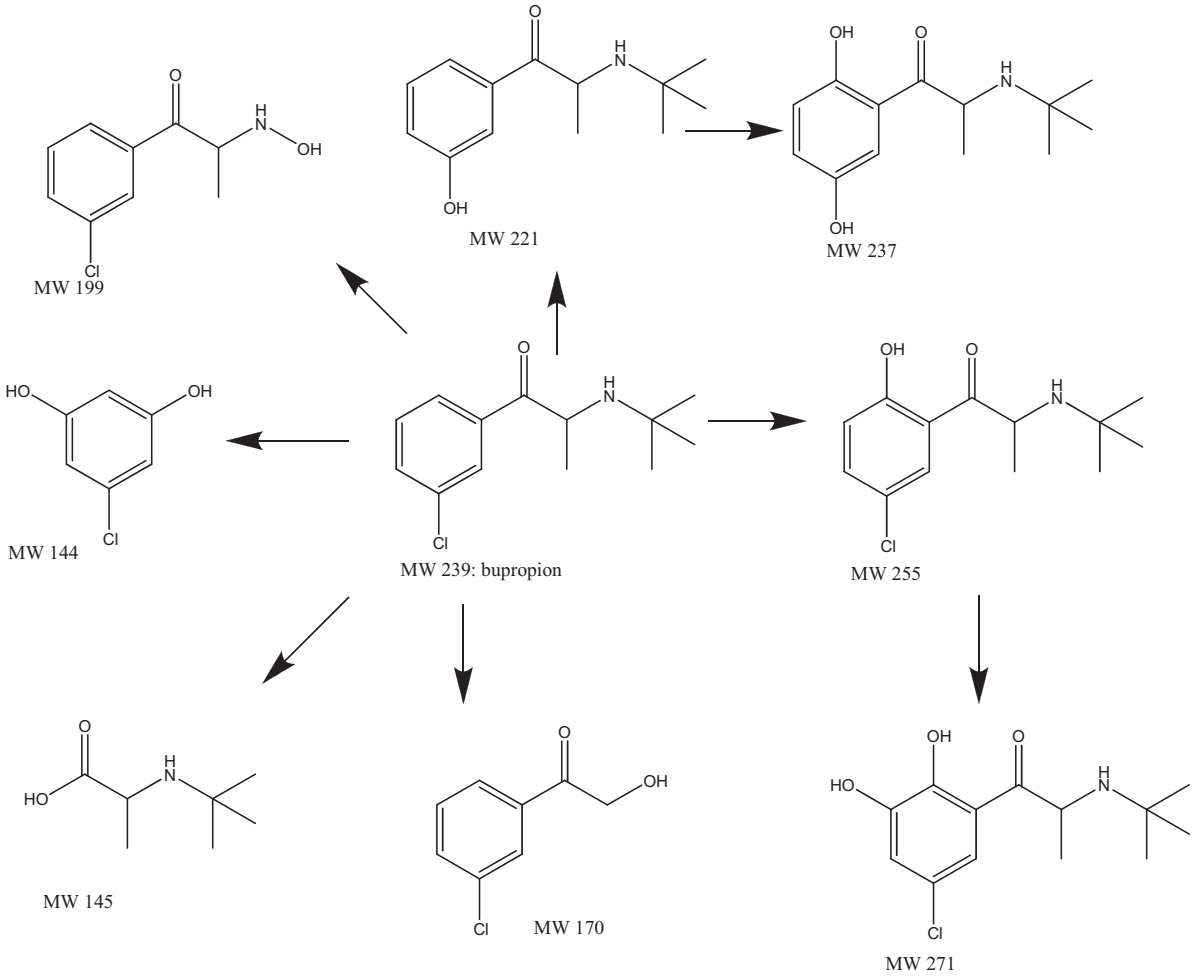


Fig. 10. Hydroxyl radical reaction products for bupropion.

fluoroquinolones [37] and beta blockers [5]. Two of the molecules undergo fragmentation when reacted with hydroxyl radicals, and in every case the fragments undergo hydroxylation as well. These products are likely to appear in any treatment plant that attempts to break down antidepressant pharmaceuticals using advanced oxidation processes involving reaction with hydroxyl radicals, and therefore merit further study, including analysis of their toxicity and environmental fate.

4. Conclusions

Of the three antidepressants studied, only duloxetine is susceptible to significant direct photolysis. Venlafaxine and bupropion, however, undergo indirect photolysis to a limited extent. The hydroxyl radical was more important in the degradation of all three compounds in water to which SRHA had been added, compared to singlet oxygen or the hydrated electron. Pathways for reaction of the antidepressants with hydroxyl radical include hydroxylation and fragmentation, in various possible combinations, and the presence of dissolved organic matter does not appear to affect the reaction efficiency. In the case of duloxetine, excited triplet state dissolved organic matter also accounts for a significant portion of the degradation.

After wastewater is discharged into the environment, the water molecules are for the most part under turbulent flow and likely to be exposed to solar irradiation in surface waters. Therefore, photochemical processes are likely to influence the fate of these compounds, and an understanding of the photochemical fate of pollutants is necessary in order to safely, efficiently and economically remove them from potential sources of potable water.

Advanced oxidation/reduction processes (AO/RPs) are currently under development to remove pharmaceuticals from water, since other treatment techniques have often proved ineffective in this regard [19,21,53–58]. The studies reported here also suggest that AO/RPs would be an effective treatment alternative for the three antidepressant compounds studied.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2012.03.049.

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