Exploring the mechanism of diphenylmethanol oxidation: A combined experimental and theoretical approach

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ABSTRACT

The mechanistic aspects of hydroxyl ($^\cdot$OH) and sulfate radical ($SO_4^{\cdot-}$) induced oxidation of diphenylmethanol (DPM) in aqueous medium has been explored using a combined experimental and theoretical approach. $^\cdot$OH initiates the generation of hydroxycyclohexadienyl-type radicals (***i***) upon reaction with DPM (λ_{max} = 330 nm; $k_2 = (1.44 \pm 0.08) \times 10^{10} \, dm^3 \, mol^{-1} \, s^{-1}$). Time-dependent density functional theory (TDDFT) calculations revealed an *ortho*-hydroxylated adduct structure to radical ***i***, which shows comparable absorbance characteristics (λ_{max} = 322 nm). High resolution mass spectrometric (HRMS) studies reveal the existence of mono- and di-hydroxylated compounds of DPM and benzophenone as the main degradation products. Hydroxylated products were derived from the radical ***i*** by either a radical-radical disproportion or a bimolecular transformation felicitated by molecular oxygen. Benzophenone (**III**) is likely originated from the radical cation (***iii***), generated as a result of one electron oxidation of DPM by $^\cdot$OH/$SO_4^{\cdot-}$, by deprotonation followed by electron and proton release.

1. Introduction

Hydroxyl radicals ($^\cdot$OH), a highly reactive non-selective radical with a standard reduction potential ($E^0(^\cdot OH,H^+/H_2O)$) of + 2.8 V_{NHE}, is the most important oxidizing species formed during the radiolysis of water [1,2]. This radical has been successfully utilized by many researchers for the degradation of organic pollutants in various advanced oxidation processes (AOPs) [3–5]. $^\cdot$OH generated by Fenton and Fenton-like reactions are reportedly involved in the oxidative damage of various biomolecules including DNA and proteins [6].

Although AOPs are proven as highly efficient methodologies to degrade intractable pollutants, these techniques might produce transformation products with similar structural, chemical and toxicological characteristics to that of the parent molecule. For example, the transformation products of many organic pollutants (for example: nonylphenol ethoxylates, chlorpyrifos, carbaryl etc.) are reported as more persistent and toxic than the parent compound [7–12]. Comprehensive investigations on the mechanism leading to the degradation of organic pollutants by $^\cdot$OH are thus very important especially in the context of

implementation of these techniques into real system. Thus, the chemical and toxicological status of all the intermediate products formed during the process needed to be monitored.

High resolution mass spectrometry (HRMS) coupled with liquid chromatography (LC), provides the highly accurate masses of the parent ion as well as the fragment ions, is regarded as an undisputed tool for the end product and metabolite profiling [3,13,14]. Some of the HRMS techniques such as Q-TOFs and Orbitraps are capable to acquire the product profile even from very complex samples without any sample purification [14–16]. Furthermore, most of the commercially available modern bench-top Q-TOF machines can achieve very low level (femtomole) sensitivity without compromising the resolving power and mass accuracy [9]. The identity of the transformation products acquired by HRMS is therefore utilized by many researchers to interpret the transient spectroscopic data recorded during their pulse radiolysis experiments [3,4,13,17]. Furthermore, structural optimizations using density functional theory (DFT) and time-dependent density functional theory (TDDFT) methods are also utilized by many authors for the accurate prediction of $^\cdot$OH reaction site, which is extremely difficult to

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locate by experimental methods, and to predict the absorbance spectra of the transients [18–21]. Another useful way to resolve the ˙OH reaction chemistry is to compare the kinetic and spectroscopic aspects of the secondary radicals (induced ˙OH) with the electron abstracted (radical cation) and hydrogen abstracted radical species generated by more specific oxidants like sulfate ($SO_4^{˙-}$), azide ($N_3^˙$) and oxide radicals ($O^{˙-}$).

Diphenylmethanol (DPM), a fundamental component of a large number of pharmaceutical preparations, has been selected as a model pollutant for the present study. DPM is an important intermediate in the synthesis of a large number of organic compounds including pharmaceuticals, perfumes and agrochemicals [22]. The photocatalytic oxidation (a well-known AOP) and reduction of this compound is previously reported [22–24]. However, the kinetic and mechanistic aspects of this reaction are not clearly elucidated. In the present work, we have mainly focused on these aspects. The kinetics and intermediate spectra of this compound was monitored by pulse radiolysis technique. The stable end-up products, even in minute concentrations, formed during the reaction were identified by HRMS analysis. Theoretical calculations by Gaussian 03 (Gaussian, Inc) [25] were also performed in order to locate the exact reaction sites of ˙OH on this compound. Additionally, a comparison on the degradation efficiency has been made between ˙OH and $SO_4^{˙-}$, which is recently recognized as a more powerful oxidant than ˙OH against a number of pollutants including atrazine [26,27]. The mechanistic aspects accomplished by these kinds of techniques serves as a basic framework for the effective application of AOPs in real water systems. Furthermore, the generation of ˙OH is highly favorable in living cells via Fenton and Fenton-like reactions [6] and hence the mechanistic aspects of biologically important molecules like DPM are very relevant.

2. Experimental

Diphenylmethanol was purchased from Aldrich chemicals and was used as received. HPLC and LC-MS grade acetonitrile were used for the HPLC and LC-Q-TOF MS analyses, respectively. All other reagents such as perchloric acid, sodium hydroxide etc. was in the highest available purities. High purity N_2O and Ar gas was used for pulse radiolysis experiments. Water collected from a Millipore Milli-Q system was used for preparing the experimental solutions throughout the study. The absorption spectra of DPM as a function of pH were recorded using a UV–VIS Spectrophotometer (UV-1700, Shimadzu).

2.1. Steady state irradiation

Steady state irradiation studies of DPM were performed on a photoreactor equipped with a medium pressure mercury lamp which emits intense light around 254 nm. Samples were removed from the photoreactor at regular time intervals and were used for further analysis.

2.2. HPLC analysis

Degradation of DPM induced by ˙OH and $SO_4^{˙-}$ were monitored by Shimadzu LC-20AD Prominence Liquid Chromatography system coupled with a Shimadzu SPD M20A Diode Array Detector (at 220 nm). An isocratic elution of acetonitrile and water (1:1) at a flow rate of $1\, mL\, min^{-1}$ against an enable C18G column (250 mm × 4.6 mm × 5 µm) was used for the chromatographic separation of the analytes. 20 µl of the sample, introduced into the chromatographic column using a Shimadzu SIL 20A HT prominence auto sampler, was used for each analysis.

2.3. LC-Q-TOF MS analysis

The transformation products of DPM induced by the reaction of ˙OH and $SO_4^{˙-}$ were identified by an Ultra Performance Liquid Chromatography (Waters Acquity H class UPLC) coupled with a

Quadrapole-Time of Flight (Q-TOF) high resolution mass spectrometer (Waters Xevo G2). Various transformation products in the irradiated samples of DPM were separated on a BEH C18 column (50 mm × 2.1 mm × 1.7 µm) using a gradient elution of solvent A (0.1% formic acid in acetonitrile) and solvent B (0.1% formic acid in water). All the chromatographic runs were performed with a mobile phase flow rate of $0.3\, mL\, min^{-1}$. Mass spectra were recorded in both positive (ESI +) and negative (ESI −) ionization mode between massby-charge (*m/z*) ranges of 50–600 Da. Electrospray ionization (ESI) technique was applied to produce the gas phase ions of different oxidation products. Leucine enkephalin, having an $[M+H]^+$ of 556.2771 and an $[M−H]^-$ of 554.2615, was used as a reference standard for correcting the mass spectra recorded by the TOF instrument [28]. The collision-induced dissociation (CID) spectra (commonly referred as MS/MS spectra) of different transformation products were recorded by fragmenting the corresponding precursor ions using high purity argon gas.

2.4. Pulse radiolysis studies

Time resolved transient spectroscopic analysis of the transient intermediates were carried out on a 7 MeV linear electron accelerator (AS & E, USA) equipped with an optical absorption detection system (Luzchem, Canada) consisting of a Cermax parallel lamp (175 W), a monochromator and a Hamamastu photomultiplier (R-7400U-04). The dose delivered per each pulse of the electron beam was determined by KSCN dosimetry as per the reported procedure of Buxton and Stuart (1995) and was found to be nearly 15 Gy per 100 ns pulse [29]. All other details of the accelerator and detection system have been published elsewhere [30].

2.5. Theoretical studies

Theoretical calculations on the parent compound as well as the intermediate radical species were performed by Gaussian 03 suite of programs. The individual structure**s** of various adduct radicals were optimized in both gas and solution phases with DFT/B3LYP method using the $6 − 31G(d,p)$ basis set. The model used for all the calculations in solution phases were polarizable continuum model (PCM). The cavity for the solute was built using Universal Force Field (UFF) radii with RMin = 0.5 and OFac = 0.8. The solution in this calculation is water with Eps = 78.39. TDDFT study (nstates = 20) was included to analyze the UV–Vis absorption spectra of the transients.

3. Results and discussion

3.1. Steady state irradiation

The sensitivity of our HPLC method for the detection of DPM was initially investigated by injecting a series of concentrations of DPM. The plot of area under the curve corresponding to the parent compound as a function of [DPM] showed a linear response between a concentration ranges from $5 \times 10^{-7}\, mol\, dm^{-3}$ to $1 \times 10^{-4}\, mol\, dm^{-3}$ (Fig. S1. Supplementary data). No significant reduction in the concentration of DPM, in the aqueous medium and dark condition (within several days) as well as in the photo-irradiated condition in the absence of $H_2O_2/K_2S_2O_8$ (within the experimental timescale), has been observed indicating the stability of this compound in the aqueous medium (data not shown).

To evaluate the efficiency of ˙OH and $SO_4^{˙-}$ against the destruction of DPM, steady state photo-irradiation experiments were carried out. A continuous supply of these radicals for the steady state experiments were produced by irradiating DPM ($1 \times 10^{-5}\, mol\, dm^{-3}$) with ultraviolet (UV) radiation in presence of H_2O_2 ($1 \times 10^{-3}\, mol\, dm^{-3}$) or $K_2S_2O_8$ ($1 \times 10^{-3}\, mol\, dm^{-3}$). The results are shown in Fig. 1. Nearly 90% transformation of the parent compound is observed within 2 and