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Photodegradation of sulfasalazine and its human metabolites in water by UV and UV/peroxydisulfate processes

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ABSTRACT

The widespread occurrence of pharmaceuticals and their metabolites in natural waters has raised great concerns about their potential risks on human health and ecological systems. This study systematically investigates the degradation of sulfasalazine (SSZ) and its two human metabolites, sulfapyridine (SPD) and 5-aminosalicylic acid (5-ASA), by UV and UV/peroxydisulfate (UV/PDS) processes. Experimental results show that SPD and 5-ASA were readily degraded upon UV 254 nm direct photolysis, with quantum yields measured to be $(8.6 \pm 0.8) \times 10^{-3}$ and $(2.4 \pm 0.1) \times 10^{-2}$ mol Einstein^{-1}, respectively. Although SSZ was resistant to direct UV photolysis, it could be effectively removed by both UV/H_2O_2 and UV/PDS processes, with fluence-based pseudo-first-order rate constants determined to be 0.0030 and 0.0038 cm^2 mJ^{-1}, respectively. Second-order rate constant between $SO_4^{\bullet-}$ and SSZ was measured as $(1.33 \pm 0.01) \times 10^9$ M^{-1}s^{-1} by competition kinetic method. A kinetic model was established for predicting the degradation rate of SSZ in the UV/PDS process. Increasing the dosage of PDS significantly enhanced the degradation of SSZ in the UV/PDS process, which can be well predicted by the developed kinetic model. Natural water constituents, such as natural organic matter (NOM) and bicarbonate (HCO_3^-), influenced the degradation of SSZ differently. The azo functional group of SSZ molecule was predicted as the reactive site susceptible to electrophilic attack by $SO_4^{\bullet-}$ by frontier electron densities (FEDs) calculations. Four intermediate products arising from azo bond cleavage and SO_2 extrusion were identified by solid phase extraction-liquid chromatography-triple quadrupole mass spectrometry (SPE-LC-MS/MS). Based on the products identified, detailed transformation pathways for SSZ degradation in the UV/PDS system were proposed. Results reveal that UV/PDS could be an efficient approach for remediation of water contaminated by SSZ and its metabolites.

1. Introduction

The widespread occurrence of pharmaceuticals and their metabolites in natural waters has recently received growing public and regulatory attention considering their potential adverse effects on human health and ecological systems (Kümmerer, 2009; Celiz et al., 2009; La Farré et al., 2008; Bonvin et al., 2012). Sulfasalazine (SSZ), also known as azulfidine, is a medicine widely prescribed for treatment of inflammatory bowel disease (e.g., ulcerative colitis and Crohn's disease) as well as rheumatoid arthritis (Volin et al., 2002). SSZ is a conjugate of sulfapyridine (SPD) and 5-aminosalicylic acid (5-ASA) linked by an azo bond (see Fig. 1 for

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Abbreviations: AOPs, advanced oxidation processes; 5-ASA, 5-aminosalicylic acid; DAD, diode array detector; DBPs, disinfection by-products; DNA, deoxyribonucleic acid; DFT, density functional theory; DOC, dissolved organic carbon; ESI, electrospray ionization; FEDs, frontier electron densities; HLB, hydrophilic-liphophilic balance; HOMO, highest occupied molecular orbital; HPLC, high performance liquid chromatography; LC-MS/MS, liquid chromatography-triple quadrupole mass spectrometry; LFP, laser flash photolysis; LP-Hg, low-pressure mercury; LUMO, lowest unoccupied molecular orbital; mTA, *m*-toluic acid; NOM, natural organic matter; PDS, peroxydisulfate; RNA, ribonucleic acid; ROS, reactive oxygen species; SPE, solid phase extraction; SPD, sulfapyridine; SRFA, Suwannee River fulvic acid; SSZ, sulfasalazine; TOC, total organic carbon; TPs, transformation products; TIC, total ion current chromatogram.

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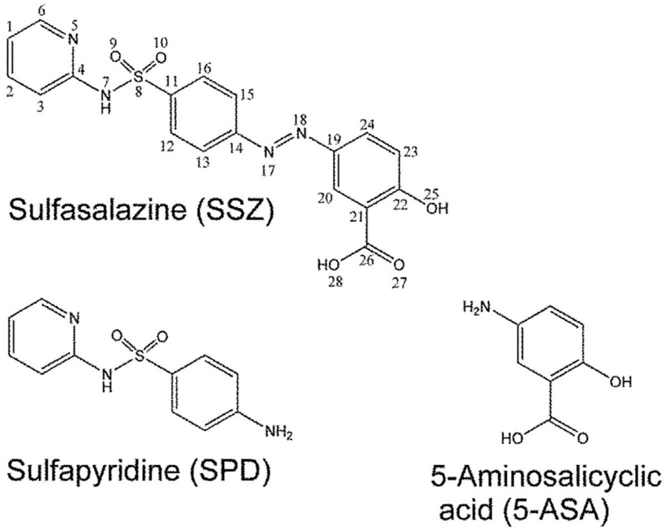

Fig. 1. Molecular structures of sulfasalazine (SSZ, $C_{18}H_{14}N_4O_5S$, CAS 599-79-1), sulfapyridine (SPD, $C_{11}H_{11}N_3O_2S$, CAS 144-83-2), and 5-aminosalicyclic acid (5-ASA, $C_7H_7NO_3$, CAS 89-57-6). The atoms of SSZ molecule are labeled with numbers for the purpose of frontier electron densities (FEDs) calculations.

molecular structures). It is metabolized by the bacterial azoreducates enzymes in the colon, reducing the azo bond and releasing SPD and 5-ASA (Chungi et al., 1989). SSZ can also be biotically/abiotically converted to SPD and 5-ASA by naturally occurring processes (Miao et al., 2004; Göbel et al., 2005). While environmental relevant concentrations of SSZ and its metabolites typically range from nanogram per liter to microgram per liter (Göbel et al., 2005; Kasprzyk-Hordern et al., 2008), their occurrence can cause subtle chronic and unpredicted effects on aquatic organisms and ecosystem (Schwarzenbach et al., 2006). For example, SSZ can induce the formation of reactive oxygen species (ROS), resulting in damage to proteins, nucleic acids and cell membranes of aquatic organisms (Linares et al., 2011). Therefore, cost-effective and environmentally friendly treatment technologies are highly desirable for elimination of SSZ and its metabolites from aqueous solutions, minimizing potential risks associated with these compounds (Fan et al., 2011).

UV-based technologies are widely applied in water and wastewater treatment for both disinfection and oxidation purpose (Pereira et al., 2007a; Canonica et al., 2008; Fatta-Kassinos et al., 2011). UV photolysis alone is capable of inactivating pathogenic bacteria, viruses, and protozoa by photochemical modification of genetic materials of the cell (deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) (Mamane et al., 2007). UV radiation can also induce direct photodegradation of organic contaminants; however, such process highly depends on irradiation intensity as well as absorption behavior and quantum yield of the target compounds (Schwarzenbach et al., 2003; Fatta-Kassinos et al., 2011). When combined with peroxides, such as peroxydisulfate (PDS) and hydrogen peroxide (H_2O_2), UV radiation can generates highly reactive radicals, e.g., sulfate radical ($SO_4^{\bullet -}$) and hydroxyl radical (HO•), via homolytic cleavage of peroxide bond (Anipsitakis and Dionysiou, 2004; Antoniou et al., 2010a). Both $SO_4^{\bullet -}$ and HO• have high standard redox potentials ($SO_4^{\bullet -}$, 2.5–3.1 V; HO•, 1.8–2.7 V) and can destruct a broad range of organic compounds, with second-order rate constants typically ranging from 10^6 to 10^{10} $M^{-1}s^{-1}$ (Buxton et al., 1988; Neta et al., 1988; Pignatello et al., 2006; Tistonaki et al., 2010). Such UV/peroxide processes, also known as UV-based advanced oxidation processes (UV-AOPs), attract growing interest in water treatment engineering. Early studies have reported high efficiency of UV photolysis and UV-AOPs for removing of various organic contaminants in water and wastewater, such as herbicides (Khan et al., 2013, 2014; Luo et al., 2016; Lutze et al., 2015), pesticides (Shah et al., 2013; Khan et al., 2016), endocrine disrupting chemicals (Lau et al., 2007; Sharma et al., 2015), pharmaceuticals (Duan et al., 2017; Zhang et al., 2015; Deng et al., 2013; Tan et al., 2013; Kwon et al., 2015), cyanotoxins (Antoniou et al., 2010a, 2010b; He et al., 2013, 2014), and odor- and taste-causing compounds (Xie et al., 2015; Luo et al., 2016). UV-based technologies bear several advantages over conventional water treatment processes, such as coagulation and chlorination, because there are no disinfection by-products (DBPs) formation, chemical-free, and no sludge production (Anipsitakis and Dionysiou, 2004; Antoniou et al., 2010a). In particular, UV/PDS appears to be more efficient for eliminating organic contaminants due to its high quantum yield of $SO_4^{\bullet -}$ (1.4–1.8 for PDS and 1.0 for H_2O_2 at 254 nm) (Khan et al., 2013; Xiao et al., 2016). In addition, $SO_4^{\bullet -}$ is a single electron oxidant that reacts selectively with organics predominantly through electron-transfer mechanism (Neta et al., 1977, 1988), enabling UV/PDS process more suitable for destruction of certain recalcitrant contaminants such as perfluorooctanoic acid (Qian et al., 2016).

Naturally occurring species in waters have significant impacts on UV and UV-AOPs (Wols et al., 2013; Lutze et al., 2015; Zhang et al., 2017). These species, such as natural organic matter (NOM) and bicarbonate (HCO_3^-), can screen UV light and/or scavenge reactive radicals by serving as inner filters and/or radical scavengers and, thus, may reduce the removal efficiency of target compounds (Lutze et al., 2015; Zhang et al., 2015). Therefore, understanding the influence of these constituents facilitates practical application of UV and UV-AOPs to optimize the removal of contaminants. Kinetic modeling is a valuable tool for assessing the effects of water constituents and quantifying the efficiency of UV and UV-AOPs (Xie et al., 2015; Luo et al., 2016). Yao et al. (2013) developed a steady-state kinetic model which successfully predicted the impact of water constituents on ionophore antibiotics degradation by UV/H_2O_2 and determined the optimal H_2O_2 dosage. Generally, the degradation of organic contaminants by UV and UV-AOPs can generate a series of intermediates/products with increasing or decreasing toxicity (Yuan et al., 2011; Zhang et al., 2016; Xu et al., 2017). Identification of these intermediates/products provides insights into the reaction mechanisms and pathways of contaminants, which is essential for risk assessment (Chen et al., 2016; Zhou et al., 2017c).

Up to now, photochemical degradation of SPD has been investigated by several researchers (García-Galán et al., 2012, 2016; Challis et al., 2013; Xu et al., 2014); however, little is currently known concerning the UV and UV/PDS-based degradation of SSZ and 5-ASA. Therefore, the main purpose of this contribution is 1) to investigate the efficacy of UV photolysis and UV/PDS advanced oxidation of SSZ in aqueous solution; 2) to compare the degradation efficiency of SSZ with those of SPD and 5-ASA by both UV and UV/PDS processes; 3) to develop a kinetic model to predict the degradation behavior of SSZ by UV/PDS process and systematically investigate the influence of natural water constituents such as NOM and HCO_3^-; and 4) to identify the intermediate products of SSZ generated in the UV/PDS process and propose reaction pathways. Results obtained herein may provide useful information for applying UV and UV/PDS to degrade pharmaceuticals and their metabolites in natural water matrix.

2. Materials and methods

2.1. Chemicals and materials

Chemicals, suppliers, and purities are listed in Supplementary Material (SM hereafter), Text S1. All stock solutions were prepared by dissolving the chemical agents into Milli-Q water (18 MΩ