Photochemical fate of quaternary ammonium compounds in river water†

Priya I. Hora and William A. Arnold†*

Quaternary ammonium compounds (QACs) are not completely removed during wastewater treatment and are frequently detected in surface waters and sediments. The photochemical transformation of QACs has not been thoroughly investigated as a potential degradation pathway affecting their fate in the environment. Kinetic studies of common QACs with and without aromatic groups under simulated and natural sunlight conditions were performed with model sensitizers and dissolved organic matter to estimate photochemical half-lives in the aquatic environment. All QACs investigated react with hydroxyl radicals at diffusion-controlled rates (~2.9 × 10⁹ to 1.2 × 10¹⁰ M⁻¹ s⁻¹). Benzathonium reacted via direct photolysis (Φ₁₂₅₇,outdoor = 1.7 × 10⁻² (mol Ei⁻¹)). Benzathonium also reacted with the triplet excited state model sensitizer 2-acetylnaphthalene, but evidence suggests this reaction pathway is unimportant in natural waters due to faster quenching of the triplet 2-acetylnaphthalene by oxygen. Reactivity with singlet oxygen for the QACs was minimal. Overall, reactions with hydroxyl radicals will dominate over direct photolysis due to limited spectral overlap of sunlight emission and QAC absorbance. Photolysis half-lives are predicted to be 12 to 94 days, indicating slow abiotic degradation in surface water.

Environmental significance
Quaternary ammonium compounds (QACs) are extensively used worldwide. The photochemical fate of QACs in aquatic environments is not fully understood. The present study comparatively evaluates the contributions of direct and indirect photolysis on the transformation of five QACs in the environment. Through a series of sensitizer experiments in buffer and river water experiments under simulated and natural sunlight, this work reveals that QACs are susceptible to indirect photolysis by hydroxyl radicals, but direct photolysis is only important for benzathonium. This study aids in assessing the role of photolysis in the overall fate of QACs in surface waters.

1. Introduction
Since the late 1930s, quaternary ammonium compounds (QACs) have been a widely used class of chemicals, chemical mixtures, and additives in a variety of industrial, agricultural, clinical, and consumer product applications.¹–³ Some QACs are designated by the U.S. Environmental Protection Agency and the Organization for Economic Cooperation and Development as high production volume chemicals (≥1 million pounds per year imported or manufactured). An extensive primary use of QACs is as cationic surfactants.⁴–⁶ QACs are used in fabric softeners, antistatic agents, commercial disinfectants, sanitizers, antimicrobials, biocides, herbicides, pesticides, food preservatives, detergents, and phase transfer agents, and active ingredients in pharmaceuticals, cosmetics, and personal care products such as shampoos and antibacterial soaps.¹,²,⁶–⁷ QACs are also used as lytic biocides, corrosion inhibitors, and clay stabilizers in hydraulic fracturing.⁶,⁸–¹⁰

QACs contain at least one hydrophobic hydrocarbon chain bonded to a positively charged quaternary nitrogen atom and have other alkyl groups that tend to be mostly short-chain substituents such as methyl or benzyl functional groups.³,¹¹ The central nitrogen is covalently bonded to four carbon-containing “R”-substituents (R₄N⁺). There are three major classes of QACs: benzylalkyl dimethyl ammonium compounds (BACs), alkyltrimethyl ammonium compounds (ATMACs), and dialkyldimethyl ammonium compounds (DADMACs).

QACs are introduced into aquatic ecosystems through point source pollution and the discharge of effluents from wastewater treatment plants and are considered emerging pollutants.¹,²,⁷,¹¹–¹⁶ QACs have been detected in environmental compartments ranging from surface water to sediments and may be found in septic and sewage impacted areas.⁷,¹¹,¹⁷–¹⁹ The worldwide average concentration of QACs in domestic wastewater, treated effluents, and surface water has been reported to be approximately 500 µg L⁻¹, 50 µg L⁻¹, and 40 µg L⁻¹, respectively.¹,²,¹²,¹⁰ The three QAC classes most frequently detected in the environment are: DADMACs with alkyl chain lengths
from C₈ to C₁₈. ATMACs with alkyl chain lengths from C₁₂ to C₁₈, and BACs with alkyl chain lengths from C₁₂ to C₁₈. Approximately 75% of QACs used annually are released into wastewater treatment systems and BAC is the most frequently found QAC group worldwide in municipal wastewater effluents at concentrations ranging from 20 to 300 µg L⁻¹. Although a large fraction of QACs are removed during the wastewater treatment process, QACs are still detected in aquatic environments, especially at higher concentrations in locations downstream of wastewater effluent discharge.

Understanding the fate of QACs is important because an estimated 32.5% of QACs produced worldwide are released into the environment, and they retain their biocidal properties after application. QACs are known to be aerobically biodegradable, but the extent of biodegradation is variable. Based on laboratory studies, rates can vary from hours to months and depend on factors such as QAC structure, concentration, and microbial acclimation. Results from some of these studies suggest that biodegradation rates decrease with increasing hydrophobic alkyl chain length. Additionally, the data indicate that QACs with a benzyl group have decreased biodegradation. Moreover, while water-soluble, QACs have a strong tendency to sorb to organic matter in water bodies due to favorable hydrophobic and electrostatic interactions, which might reduce bioavailability and inhibit biodegradation. QACs have been detected in sediments at concentrations higher than in the aqueous phase, suggesting that QACs are environmentally persistent and their transport and fate are dependent upon association with organic matter in surface waters.

Ecotoxicological effective concentrations (EC₅₀) of QACs reported for various fish, algae, crustaceans, daphnia, rotifers, and bacterial, and protozoan species range from tens of µg L⁻¹ to mg L⁻¹. While QACs generally have not been considered acutely toxic to aquatic organisms based on reported surface water concentrations below many EC₅₀ values, more research is needed. QACs might still pose cumulative chronic effects. Concerns about the detection of QACs in the environment stem from the possibility that prolonged exposure to sub-inhibitory QAC concentrations co-selects for antibiotic resistant bacteria.

The photochemical behavior of QACs in natural environments is still not well understood. BACs are considered stable to direct photodegradation. Direct photolysis occurs when a contaminant undergoes transformation, such as breaking of bonds, resulting from directly absorbing light energy. Many QACs lack chromophoric functional groups or exhibit poor absorption of light in the visible spectrum; thus, direct photolysis processes may be limited in natural waters. Indirect photolysis, facilitated by QAC association with dissolved organic matter (DOM), could be an important and understudied attenuation mechanism. Indirect photolysis occurs when a photosensitizer such as organic matter in natural waters absorbs light energy, becomes electronically excited, and subsequently reacts with a contaminant or produces transient photochemically produced reactive intermediates (PPRIs) that are energetically capable of transforming target contaminants. PPRIs, including reactive oxygen species (ROS), such as hydroxyl radicals (·OH) and singlet oxygen (¹O₂), and non-ROS excited triplet states of DOM (³DOM*), react with contaminants in natural systems thus enhancing degradation and increasing phototransformation rates. QACs may sorb to DOM, which is ubiquitous in natural waters, and this interaction affects their distribution, transformation, and bioavailability. In aquatic systems, DOM may act as a sink for QACs and as a photosensitizer. For some hydrophobic compounds, attachment to DOM can expose the pollutant to heterogeneous microenvironments with high concentrations of PPRIs that accelerate degradation, or alternatively, this association could shield compounds from light, inhibiting reactions.

This study examines the photochemical fate of 5 QACs in surface waters and addresses gaps in knowledge on biocide degradation. By conducting experiments in buffered ultrapure water using sensitizers and radical quenchers and in Mississippi River water, the relative contributions of direct and indirect photolysis for each QAC are determined. Kinetic studies allow for calculation of second-order reaction rate constants in radical-mediated processes, estimation of quantum yields where relevant, and estimation of environmental half-lives in natural waters.

2. Materials and methods

2.1 Chemicals and reagents

The quaternary ammonium compounds used in this study were: benzylidimethyl-n-dodecylammonium chloride (C₁₂-BAC, 98%, Alfa Aesar), benzyldimethyltetradecyl-ammonium chloride hydrate (C₁₄-BAC, 99%, TCI America), benzethonium chloride (BZT, 99%, TCI America), didecyldimethylammonium bromide (C₁₂-DABMA, 99.9%, Santa Cruz Biotechnology), and didecyltrimethyl ammonium bromide (C₁₂-ATMA, 99%, Acros Organics). Structures are shown in the ESI Table S1. Many QACs, including surfactants, para-chlorobenzoic acid (pCBA, 98%, Acros Organics) was used as an ·OH sensitizer, Rose Bengal (RB, dye content 95%, Sigma-Aldrich) and 2-acetyl-naphthaldehyde (2-AN, 99%, Alfa Aesar), were used as ¹O₂ sensitizers, para-chlorobenzoic acid (pCBA, 98%, Acros Organics) was used as an ·OH probe, furfuryl alcohol (FFA, 98%, Alfa Aesar) was used as a quenching agent for triplet excited states. Histidine (His, 99%, Sigma Aldrich) was used as an ¹O₂ quencher, and sorbic acid (99%, Alfa Aesar) was used as a quenching agent for triplet excited states. Hydrogen peroxide (H₂O₂, 30%, Fisher) was used as an ·OH probe, HPLC grade 2-propyl alcohol (IPA, 99.9%, Fisher) was used as an actinometer, and sorbic acid (99%, Alfa Aesar) was used as a quenching agent for triplet excited states. p-Nitroacetophenone and pyridine (PNAP-PYR) were used as an actinometer, and tetrapentylammonium bromide (C₅-TAA, 99%, Sigma Aldrich) was used as an internal standard for mass spectrometry analysis. Sodium phosphate monobasic monohydrate (98%, Sigma Aldrich) and tetrapentylammonium bromide (C₅-TAA, 99%, Sigma Aldrich) were used as an internal standard for mass spectrometry analysis. Sodium phosphate monobasic monohydrate (98%, Fisher), sodium phosphate dibasic anhydrous (99%, J.T. Baker), ammonium acetate (97%, Macron), sodium hydroxide (98%, Macron), hydrochloric acid (35%, TraceMetal Grade, Fisher), o-phosphoric acid (85%, HPLC Grade, Fisher), and phosphoric acid (85%, HPLC Grade, Fisher).
River water pH was measured using a Thermo Scienti-

cific pH probe (calibrated with pH 4, 7, and 10 standard solutions

analytical methods

Ultraviolet-visible absorbance of river water as well as aqueous

Absorption spectra

Analytical methods

Concentrations of QACs with an aromatic group (C12-BAC, C14-

Model sensitizer photochemical experiments

Experiments were performed to determine the reactivity of QACs with 'OH using H2O2 and with O2 using RB and 2-AN.

Singlet oxygen experiments were conducted in a similar

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state reduction potential, $E^o (S/S^-) = -1.48 \text{ V}_{\text{SHE}}$; triplet energy, $E_T = 249 \text{ kJ mol}^{-1}$; triplet state reduction potential, $E^o (^3S{^*}/S^-) = 1.10 \text{ V}_{\text{SHE}}$; $^1\text{O}_2$ quantum yield $\Phi_k = 0.71$. Deoxygenated solutions were prepared in an anaerobic glove bag (97% N$_2$/3% H$_2$, Pd catalyst, Coy Laboratory Products Inc.) by spiking aqueous stocks (in deoxygenated ultrapure water) of BZT, 2-AN, and FFA in deoxygenated pH7 10 mM phosphate buffer, which was sparged with N$_2$ gas for 2 hours. The solution was placed into quartz test tubes and further bubbled with N$_2$ outside of the glove bag for 5–10 minutes prior to being sealed with foil and rubber septa caps. The deoxygenated tubes were sampled sacrificially at 20 and 50 minutes. Another experiment with BZT in deoxygenated phosphate buffer was run with 1 mM sorbic acid to quench triplets. Sorbic acid was stirred overnight on a heated stir plate and then sonicated and degassed with application of vacuum for 10–20 minutes at 30–40 °C before being brought into the glove bag. Other solutions were prepared as above, and all sample solutions were bubbled with N$_2$ outside of the glove bag for 30 minutes prior to being dispensed into test tubes under a nitrogen blanket and sealed with foil and rubber septa caps. Tubes were sampled sacrificially after 10, 20, 30, 40, and 50 minutes.

Steady-state concentrations of hydroxyl radicals ([‘OH]$_{ss}$) and singlet oxygen ([‘O$_2$]$_{ss}$) were calculated from the ratio of the measured pseudo-first-order rate constant ($k_{obs}$), determined via linear regression, and the bimolecular reaction rate constant of pCBA with ‘OH ($k_{\text{OH-pCBA}} = 5 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$) and FFA with ‘O$_2$ ($k_{\text{O}_2} = 1.17 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ at 30 °C). Direct photolysis losses of the probes were negligible. Assuming a first-order kinetic dependence on each QAC and pCBA and that the reactions proceed independently, bimolecular reaction rate constants of QACs with ‘OH ($k_{\text{OH-QAC}}$) were derived using competition kinetics according to eqn (1).

$$\ln \left( \frac{[\text{QAC}]}{[\text{QAC}_0]} \right) = \ln \left( \frac{[\text{pCBA}]}{[\text{pCBA}_0]} \right) \frac{k_{\text{OH-QAC}}}{k_{\text{OH-pCBA}}} \quad (1)$$

The rate constants for the respective QACs were obtained from linear regressions of logarithmic plots of normalized QAC versus pCBA concentrations in the same tube.

### 2.6 Simulated and outdoor photochemical experiments in river water

QAC photolysis experiments were performed on Mississippi River water and phosphate buffer under simulated and natural sunlight to assess the relative importance of direct photolysis and indirect photochemical transformation due to PPRIs. The radical-specific probe pCBA was used for the quantification of ‘OH steady-state concentrations in the same tube. Direct photolysis controls were performed for all QACs and pCBA in phosphate buffer solutions (10 mM, pH 7.0), and dark control experiments for QACs and pCBA in river water were performed in tubes wrapped with aluminum foil. River water solutions spiked with 1% IPA as a radical quencher were concurrently irradiated to evaluate the importance of indirect photolysis processes involving ‘OH. Time resolved samples of 200 or 500 μL were removed for HPLC analysis to determine reaction kinetics.

For simulated sunlight experiments, C$_{12}$ and C$_{14}$-BAC and BZT were photolyzed in filtered Mississippi River water using a solar simulator. The light intensity was set to 765 W m$^{-2}$, and samples were taken every 5 hours. All experiments were run in duplicate. For outdoor natural sunlight experiments, C$_{12}$ and C$_{14}$-BAC and BZT were photolyzed in filtered Mississippi River water collected on June 5, 2018 over a total of 26.8 hours from June 28, 2018 to July 6, 2018 (Table S4† summarizes the exposures) on the rooftop of the University of Minnesota Mechanical Engineering building (latitude: 44°58'30"N, longitude: 93°14'1"W, elevation: 860 ft, azimuth: 218°SW).

Aliquots of 6–8 mL initial volume reaction solutions in 10 mL quartz test tubes (13 mm o.d. and 11 mm i.d.) were sealed with pre-combusted aluminum foil squares and then rubber septa caps. The test tubes were irradiated at a 30° angle from the horizontal. Initial QAC and probe concentrations were nominally 10 μM, allowing for direct monitoring of reactant and probe compound concentrations and minimization of light screening.

The chemical actinometer PNAP-PYR was simultaneously irradiated during simulated and natural sunlight river water experiments to estimate the spectral irradiance of the light source, calculate direct photolysis quantum yields for QACs at low optical density, and plot long duration experimental data by dose via actinometer loss to compare laboratory and outdoor experiments. The PNAP-PYR actinometer was chosen because the half-life of the QACs was expected to be greater than 4 hours based on preliminary experiments. The concentrations of pyridine were set using relationships in Leifer$^{53}$ such that the actinometer loss rate would occur over the same time scale as the QAC loss. The spectral irradiance of the solar simulator at wavelengths 276–400 nm was estimated using a bimolecular solution of 47.2 mM pyridine added to 10.7 μM p-nitroacetophenone for a desired half-life of 17 hours in river water experiments. For rooftop experiments, a 11.4 μM PNAP/52.3 mM pyridine solution was used. The molar absorptivity of PNAP ($\varepsilon_{\text{PNAP}}$) was calculated by linear regression of absorbance measurements of 3 analytical standards (concentrations 5, 10, and 15 μM) prepared in Milli-Q with trace acetanilide.

The SMARTS 2.9.5 model$^{59,61}$ was used to calculate the solar spectral irradiance (Fig. S1†) over the time course of outdoor experiments. Salient inputs are summarized in ESI Table S5.† Global tilted irradiances were calculated for each solar hour in an experimental day, summed, and divided by the total exposure hours for each day. The daily irradiances were then averaged for quantum yield calculations.

Direct photolysis quantum yields were calculated following the methods outlined in Dulin and Mill$^{52}$ and Leifer$^{53}$ with the updated PNAP-PYR quantum yield relationship published by Laszakovits et al.,$^{62}$ summarized by eqn (2).

$$\phi_{\text{dc}} = \frac{\sum_j (I_j \varepsilon_{j,k}) \phi_{\text{d}}}{\sum_j (I_j \varepsilon_{j,k}) \phi_{\text{d}}} \quad (2)$$
$I_\lambda$ = the irradiance (intensity) of incident light in einsteins m$^{-2}$ s$^{-1}$ at a fixed wavelength $\lambda$. $e_\lambda$ = the decadic molar absorption coefficient of the actinometer (a) or the compound (c) in M$^{-1}$ m$^{-1}$. The molar absorptivity of the QAC cation was determined by measuring the absorption spectra of a 100 $\mu$m solution in buffer and subtracting the absorption of an equivalent concentration of the counter anion (100 $\mu$m NaCl or NaBr) as a blank. $\phi_{da} = \phi_{PNAP} = 0.0074[pyr] + 1.1 \times 10^{-5} \frac{k_{de}}{k_{da}}$ = the slope of the logarithmic plot of direct photodegradation of the compound versus actinometer determined by linear regression. The wavelength range was 276 to 400 nm for the solar simulator and 280 to 400 nm for outdoor experiments.

2.7 Data analysis

Data points from replicate experiments were plotted individually. The slope of the regression lines and their standard error were used to calculate the required slopes/reaction rate constants and the associated 95% confidence intervals, respectively. Linear fits and generation of rate constants, standard errors of slopes, and 95% confidence intervals were performed with Origin, Version 2017 (OriginLab Corporation, Northampton, MA, USA).

3. Results and discussion

3.1 Reactivity of QACs with 'OH from H$_2$O$_2$ sensitizer experiments

Based on previous work with ionic liquids,63 'OH was hypothesized to be an important PPRI for the indirect photochemical transformation of QACs. Competition kinetics experiments were conducted with H$_2$O$_2$ and pCBA to determine bimolecular reaction rate constants between QACs and 'OH ($k_{OH, QAC}$). Fig. 1 shows the natural log of the ratio of concentration normalized by the initial concentration of QACs during a solar simulator irradiation experiment with H$_2$O$_2$ producing 'OH. The C12-ATMA H$_2$O$_2$ 40 minute data points (Fig. 1D) were treated as outliers due to anomalous instrumental measurements, indicated by open symbols, and excluded from the ensuing regression and analysis. For all the compounds studied, photolysis in the presence of 'OH follows pseudo-first order kinetics ($r^2$ ≥ 0.83). Dark controls dosed with H$_2$O$_2$ showed no significant change in QAC concentration. Quantification of steady-state 'OH concentrations was done using pCBA (Fig. S2 and Table S6f).

Fig. 2 shows the log-log plot of concentrations of the 5 QACs versus that of pCBA. Using the slopes of the linear regressions in Fig. 2 and the bimolecular reaction rate constant of pCBA with 'OH, $k_{OH, QAC}$ values were calculated for the QACs using eqn (1) (Table 1).

The results demonstrate that the QACs studied react with 'OH at or near the diffusion-controlled limit (i.e., $k_{OH, L} = 5 \times 10^9 \times 10^{-10}$ M$^{-1}$ s$^{-1}$), which is the case for many organic contaminants.57,64 The hydroxyl radical reacts unselectively with most organic compounds and reactions occur at different functional groups. Typically, 'OH behaves as an electrophile and reacts with organic pollutants in two ways: (1) OH group addition to an aromatic ring or a double bond and (2) hydrogen atom abstraction from aliphatic carbon-hydrogen bonds.57,64

The structural differences of the studied QACs did not significantly affect the bimolecular rate constant, except the reaction between DADMA and 'OH is about an order of magnitude lower than for the other compounds.

Similar to imidazolium cations,63 there was a slight trend seen for increasing $k_{OH, QAC}$ with the increasing side chain length of C12 and C14-BAC though the values are within error. For C12-DADMA, where reaction with 'OH only occurs via H atom abstraction at C-H bonds in the side chains, rates were smaller than for BACs and BZT, and C12-ATMA. The exchange of a methyl group (ATMA) for a 12 carbon alkyl chain (DADMA) noticeably slows the reaction kinetics. The alkoxy groups in BZT have both inductive electron withdrawing and resonance electron-donating effects. The hydroxyl radical reacts rapidly with compounds containing aromatic rings with electron-donating substituents, and addition reactions still occur at appreciable rates in the presence of electron-withdrawing groups.64 The coincidence in rates for the BACs, BZT, and C12-ATMA suggests that H atom abstraction at C-H bonds in the side chain contributes to the overall reaction of BACs and BZT with 'OH in addition to any reaction at the ring.

3.2 Assessing reactivity with other PPRIs

To further explore the role of specific PPRIs in QAC degradation in the presence of DOM and more definitively rule out additional pathways, sensitizer experiments were conducted to assess reactivity with 1O$_2$ and triplet excited states. Because 1O$_2$ is a selective electrophile preferentially reacting with electron-rich functional groups like sulfides, phenols, amines, and aromatic compounds, anilines, furans, and other electron-rich heterocycles,56,65,66 it was hypothesized QACs would have limited interaction with this reactive oxygen species. Moreover, because DOM can be a microheterogeneous environment in which 1O$_2$ potentially reaches higher steady-state concentrations58,67 and QACs will associate with DOM, enhanced reactivity might occur if in fact they do react with 1O$_2$.

Experiments with RB showed no reaction between C12-BAC (Fig. S3A) and 1O$_2$ (FFA was used to measure the bulk concentration of 1O$_2$ - [1O$_2$]$_{bulk}$ = (3.9 ± 1.2) × 10$^{-12}$ M) (Fig. S3B, Table S7†) under air saturated conditions, and there was no statistically significant difference between the pseudo-first-order rate constant for C12-BAC loss with RB and the histidine quenched and dark controls. No loss of C12-BAC was observed in the deoxygenated control as well, indicating no reactivity with triplet excited states of RB.

BZT exhibited possible reactivity with the triplet excited state of RB based on decay in the histidine quenched control, and BZT loss in the dark control suggested that BZT was also potentially reacting with RB (Fig. S4†). Additional control experiments (not shown) indicated that BZT interacts with RB under ambient, dark conditions and therefore a different 1O$_2$ sensitizer, 2-AN, which is also a model 3DOM* sensitizer, was used.
The experiments with BZT and 2-AN illustrated minimal BZT loss due to 1O2 (Fig. S5A†), and there was no statistically significant difference between the 2-AN results and the dark control and the histidine control where 1O2 is quenched. A deoxygenated control experiment was also conducted. Interestingly, in the deoxygenated solution containing 2-AN, BZT exhibited an approximately 84% decrease after 50 minutes of irradiation. The addition of sorbic acid, which quenches triplet-excited states (with energy >200 kJ mol\(^{-1}\)) of organic compounds, to the deoxygenated 2-AN solution slowed the reaction by 95%. These results indicate that BZT reacts with 2-AN. FFA also reacted in the presence of 2-AN, but degassing the 2-AN solution resulted in a 23% decrease in the pseudo-first-order rate constant of FFA compared to FFA in an air-saturated atmosphere.

**Fig. 1** Phototransformation over time of: C\(_{12}\)-BAC (A), BZT (B), C\(_{14}\)-BAC (C), C\(_{12}\)-ATMA (D), and C\(_{12}\)-DADMA (E) in the presence of pCBA under simulated sunlight in phosphate buffer (direct, black squares), with 1 mM hydrogen peroxide (H\(_2\)O\(_2\), red circles), H\(_2\)O\(_2\) dark control (dark, green triangle), and H\(_2\)O\(_2\) with 1% isopropanol (IPA, blue upside down triangle). Open symbols denote outliers.
solution (Fig. S5b†), indicating a role for both $^1\text{O}_2$ and $^3\text{A}^*\text{N}$
Furthermore, minimal loss of FFA was observed in the deoxy-
genated solution upon addition of sorbic acid, reiterating that
FFA is susceptible to degradation by organic triplets.\textsuperscript{22,39}.
Together, these results indicate that BZT does react with $^3\text{A}^*\text{N}$, but
the reaction only occurs in the absence of oxygen, meaning
quenching of the triplets by oxygen is faster than the reaction
with BZT. Thus, BZT reaction with triplet excited state organic
matter will likely be unimportant in environmental systems
because dissolved oxygen in surface waters will efficiently
scavenge triplets before they react with BZT.

3.3 Photochemical transformation of BACs in river water
under simulated and natural sunlight
The transformation of BACs was then investigated in the
presence of DOM in river water. Based on their chemical
structures, no other processes besides reactivity with $^\text{OH}$ would occur to transform ATMA and DADMA, and further
experiments were not conducted in river water. Fig. 3A and B
show the time course of C\textsubscript{12}-BAC and C\textsubscript{14}-BAC concentrations
in phosphate buffer and Mississippi River water in the solar
simulator. The tubes were irradiated for a total of 30 hours and
this exposure was almost continuous with tubes being
removed after 5 or 10 hour increments for sampling and then
being returned to resume irradiation in the solar simulator.
The loss in river water exhibits pseudo-first-order kinetics as
attested to by logarithmic plots for QAC photolysis versus
actinometer loss (Fig. S6†). To evaluate the oxidation of BACs
by $^\text{OH}$, the probe pCBA was added to each MRW tube with
BAC, allowing for competition kinetics and quantification of
$[^\text{OH}]_{\text{aq}}$.
For C\textsubscript{12}-BAC, 9% loss of the compound was seen in the direct
photolysis control and 4% in the IPA quenched control. No
apparent loss was exhibited in the dark control; in fact, a slight
increase was observed possibly due to evaporation or variation
in analytical reproducibility. The slopes for the direct ($k_{\text{direct}}$ = $(2 \pm 1) \times 10^{-3}$ h\textsuperscript{-1}) and IPA quenched ($k_{\text{IPA}} = (1.7 \pm 0.3) \times 10^{-3}$
h\textsuperscript{-1}) controls were within error. Estimating an indirect pseudo-
first-order rate constant from the bimolecular reaction rate
constant determined from H\textsubscript{2}O\textsubscript{2} sensitizer experiments and the
calculated $[^\text{OH}]_{\text{aq}}$ from pCBA loss in MRW (Table 1) gives $(2.7 \pm 0.3) \times 10^{-2}$ h\textsuperscript{-1}, which is nearly identical to the overall rate
constant for C\textsubscript{12}-BAC degradation in MRW ($(2.9 \pm 0.4) \times 10^{-2}$
h\textsuperscript{-1} (Table S8†)), reaffirming that the loss seen in the MRW is
due to the reaction with $^\text{OH}$.
For C\textsubscript{14}-BAC, a slight increase was observed in the direct
control possibly from evaporation in the solar simulator or
instrumental error in the measurements. The data in the direct,
dark, and IPA quenched controls had consistent trends from
5 to 30 hours. While C\textsubscript{14}-BAC exhibited an average 14% and 18%
decrease from the initial concentration in the dark and IPA
quenched controls, respectively, the slopes ($k_{\text{dark}} = (3 \pm 3) \times$
$10^{-2}$ h\textsuperscript{-1} and $k_{\text{IPA}} = (5 \pm 3) \times 10^{-2}$ h\textsuperscript{-1}) demonstrate negligible
depletion in these controls compared to the loss in MRW. The
overall rate constant for C\textsubscript{14}-BAC degradation in MRW was $k_{\text{MRW}}$
= $(2.8 \pm 0.6) \times 10^{-2}$ h\textsuperscript{-1}, which agrees with the estimated
pseudo-first-order reaction rate constant for C\textsubscript{14}-BAC loss due to
the reaction with $^\text{OH}$ ($(2.9 \pm 0.4) \times 10^{-2}$ h\textsuperscript{-1}).
Photolysis proceeded faster in the presence of
dissolved organic matter, indicating the importance of
indirect photolysis (Table S8†). The addition of
the radical inhibitor IPA reduced the photodegradation rates
substantially in MRW for C\textsubscript{12} ($k_{\text{IPA}} = (6 \pm 1) \times 10^{-2}$) and C\textsubscript{14}:

<table>
<thead>
<tr>
<th>QAC</th>
<th>Hydrogen peroxide \ ($k_{\text{OH, QAC}}$ (M\textsuperscript{-1} s\textsuperscript{-1}))</th>
<th>Solar simulator, river water \ ($[^\text{OH}]_{\text{aq}}$ (M))</th>
<th>Outdoors, river water \ ($[^\text{OH}]_{\text{aq}}$ (M))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{12}-BAC</td>
<td>$(1.1 \pm 0.1) \times 10^{10}$</td>
<td>$(7.0 \pm 0.2) \times 10^{-16}$</td>
<td>$(3.8 \pm 0.3) \times 10^{-16}$</td>
</tr>
<tr>
<td>C\textsubscript{14}-BAC</td>
<td>$(1.2 \pm 0.2) \times 10^{10}$</td>
<td>$(6.7 \pm 0.1) \times 10^{-16}$</td>
<td>$(3.8 \pm 0.3) \times 10^{-16}$</td>
</tr>
<tr>
<td>BZT</td>
<td>$(1.08 \pm 0.05) \times 10^{10}$</td>
<td>$(6.1 \pm 0.4) \times 10^{-16}$</td>
<td>$(3.9 \pm 0.4) \times 10^{-16}$</td>
</tr>
<tr>
<td>C\textsubscript{12}-ATMA</td>
<td>$(1.03 \pm 0.14) \times 10^{10}$</td>
<td>$(9.3 \pm 1.3) \times 10^{-9}$</td>
<td>$(9.4 \pm 3.2) \times 10^{0}$</td>
</tr>
<tr>
<td>C\textsubscript{12}-DADMA</td>
<td>$(2.9 \pm 1.0) \times 10^{7}$</td>
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</table>

\* Errors represent 95% confidence intervals associated with the regression slopes in Fig. 2.
The quencher results demonstrate that direct photochemical loss of BACs is likely to be relatively unimportant in natural systems and indicate that the \( ^{\text{`OH}} \) produced is responsible for BAC loss. Analogous outdoor experiments were conducted in river water to verify the transferability of indoor photolysis results for the BACs. Fig. 3C and D show the time course of C\(_{12}\)-BAC and C\(_{14}\)-BAC concentrations in phosphate buffer and Mississippi River water in natural sunlight. Logarithmic plots of BAC versus actinometer loss (Fig. S7†) indicate that outdoor photolysis also follows pseudo-first-order kinetics. \( \rho \text{CBA} \) was again added to MRW tubes.

The overall rate constant for C\(_{12}\)-BAC degradation in MRW in natural sunlight was \((2.2 \pm 0.1) \times 10^{-2} \text{ h}^{-1}\). Estimating an indirect pseudo-first-order rate constant from the bimolecular reaction rate constant determined from \( \text{H}_2\text{O}_2 \) sensitizer and solar simulator river water experiments and the calculated [\( ^{\text{`OH}} \)]\(_{\text{ss}} \) from \( \rho \text{CBA} \) loss in MRW (Table 1) gives \((1.5 \pm 0.1) \times 10^{-2} \text{ h}^{-1} \) and \((1.5 \pm 0.3) \times 10^{-2} \text{ h}^{-1} \), respectively. These estimates imply that 67 to 71% of C\(_{12}\)-BAC loss in MRW in the outdoor experiment could be attributable to the reaction with \( ^{\text{`OH}} \). IPA suppressed the reaction in river water substantially (\( k_{\text{IPA}}/k_{\text{MRW}} = (8 \pm 8) \times 10^{-2} \)). For C\(_{14}\)-BAC, the overall rate constant in MRW was \( k_{\text{MRW}} = (2.6 \pm 0.4) \times 10^{-2} \text{ h}^{-1} \). The indirect pseudo-first-order rate constant estimates ((1.6 \pm 0.3) \times 10^{-2} \text{ h}^{-1} from \( \text{H}_2\text{O}_2 \) sensitizer and \((1.6 \pm 0.4) \times 10^{-2} \text{ h}^{-1} \) from solar simulator river water experiments) suggest that 61 to 62% of C\(_{14}\)-BAC loss in MRW in the outdoor experiment could be attributable to the reaction with \( ^{\text{`OH}} \). IPA suppressed the reaction in river water, though not completely (\( k_{\text{IPA}}/k_{\text{MRW}} = (3 \pm 2) \times 10^{-1} \)). At the end of the experiment, about an 18% decrease in C\(_{14}\)-BAC concentration was seen in the quenched control and 27% in the direct control, though these losses are relatively minor compared to the losses in MRW over the same time period.

Because the overlap between the absorption spectra of the BACs and the solar spectrum is small, direct photochemical loss is slow and DOM might screen light affecting transformation rates. Additionally, BACs are hydrolytically stable. Though all C\(_{12}\)-BAC control slopes are relatively rather small and associated.
with proportionate error \(k_{\text{direct}} = (6 \pm 2) \times 10^{-3} \text{ h}^{-1}, k_{\text{IPA}} = (2 \pm 2) \times 10^{-3} \text{ h}^{-1}\), and \(k_{\text{dark}} = (8 \pm 9) \times 10^{-3} \text{ h}^{-1}\), a slight loss seems to be occurring in the MRW outdoors due to other abiotic and/or biotic mechanisms. The losses in C14-BAC are more pronounced. Slight thermal decay due to elevated temperatures outside, sorption to the walls of the test tube over the outdoor exposure period, and/or biodegradation could be occurring concomitantly with indirect photolysis to account for increased degradation in the controls.

Outdoor experiments took approximately 9 days while solar exposure time was a little over a day in total to account for weather and sunshine hours on the rooftop. While the river water was filter-sterilized prior to use in experiments and test tubes were capped, no special protocols were used to maintain sterile conditions for the entirety of the experiment. Therefore, it cannot be ruled out that the difference in predicted rate constants due to 'OH and the observed rate constant is due to biodegradation because BACs are known to be susceptible to aerobic biodegradation.\(^{3,5,70}\)

The outdoor river water (MRW) rates were thusly corrected for concentration changes in the controls by eqn (3).\(^{71}\) The indirect losses were plotted separately (MRW\(_{\text{corr}}\) in Fig. 3C and D), and the pseudo-first-order rate constants from MRW\(_{\text{corr}}\) were used to calculate bimolecular reaction rate constants with 'OH in the outdoor experiments (see below).

\[
\text{MRW}_{\text{corr}}(t) = \text{MRW}(t)e^{(-k_{\text{dark}} \times t)} \quad (3)
\]

### 3.4 BZT direct photolysis in river water under simulated and natural light

The degradation of BZT in MRW appeared to be a combination of direct and indirect photolysis (Fig. 4A) in the solar simulator. Correcting the BZT concentration measured in MRW to account for the loss due to direct photolysis using eqn (3) allowed for calculation of the indirect photolysis pseudo-first-order rate constant and for competition kinetics calculations. The indirect photolysis of BZT in river water is shown in Fig. 4 by the plotted MRW\(_{\text{corr}}\) data. The probe \(p\)CBA was used to evaluate the oxidation of BZT by 'OH, by addition to each MRW tube with BZT, allowing for competition kinetics and quantification of ['OH].

The BZT direct photolysis quantum yield from solar simulator experiments was determined using eqn (2) and the photon fluence of the solar simulator determined from actinometry and the photon irradiance provided by the manufacturer (spectral flux, \(I_0 = 5.4 \text{ Es L}^{-1} \text{ s}^{-1}\)). Fig. S8† shows the logarithmic plot of BZT direct photolysis (from both the IPA quenched and direct controls) versus the PNAP actinometer. The slope of the line determined by linear regression (1.18 for IPA vs. PNAP and 1.11 for direct vs. PNAP) was used to calculate quantum yields. \(\phi_{\text{BZT,indo,IPA}}\) was determined to be \(6.3 \times 10^{-2}\) (mol Ei\(^{-1}\)) while \(\phi_{\text{BZT,indo,di,rect}}\) was \(5.9 \times 10^{-2}\) (mol Ei\(^{-1}\)). There is good agreement between the two estimates, demonstrating that the decrease of BZT seen in the IPA quenched control is due to direct photolysis and not any other process.

Outdoor experiments were carried out to compare data generated under simulated sunlight with those generated under natural sunlight and to verify the BZT quantum yield obtained in the laboratory because quantum yield calculations are sensitive to irradiance values. For BZT sunlight experiments (Fig. 4B), BZT loss exhibited pseudo-first-order kinetics in river water as seen in the logarithmic plots for QAC photolysis versus actinometer loss (Fig. S7†). As with the solar simulator experiment, \(p\)CBA was simultaneously irradiated in the MRW tubes.

The slopes of linear regressions for the BZT quenched and direct photolysis controls were identical within error due to overlapping confidence intervals. The data points were

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**Fig. 4** Photolysis of BZT with \(p\)CBA under simulated sunlight (A) or natural sunlight (B) in phosphate buffer (direct, red squares), Mississippi River water (MRW, blue circles), MRW dark control (yellow triangle), and MRW with 1% isopropanol (IPA, green upside down triangle). Indirect photochemical loss in river water is shown by purple diamonds (MRW\(_{\text{corr}}\)). Note the top x-axis for outdoor plot B showing the total duration of the experiment.
subsequently combined and fitted using a linear fit of concatenated data in Fig. S8,† which shows the logarithmic plot of BZT direct photolysis versus actinometer loss. The direct photolysis quantum yield, \( \Phi_{\text{BZT, outdoor}} \), was determined to be \( 1.7 \times 10^{-2} \) (mol Ei\(^{-1}\)) using eqn (2), the slope of 0.21 from Fig. S8,† and the average global tilted irradiance over the timecourse of the rooftop exposures from SMARTS. The discrepancy in calculated quantum yields and half-lives can be explained by the fact that, as has been reported previously,49 though the Xe lamp has a filter that prevents the transmission of wavelengths below 290 nm, there is a bleed of wavelengths <290 nm, which introduces systematic error. This error is important for QACs like BZT which absorb weakly above 290 nm and thus direct photolysis rates are over-emphasized.22 In the terrestrial aquatic environment, direct photolysis occurs for chemicals that absorb photons at wavelengths \( \geqslant 290 \) nm because the upper atmosphere screens out solar irradiance at shorter wavelengths. Despite errors introduced by the solar simulator and differences in quantum yields due to spectral overlap, direct photolysis of BZT would still occur in the environment, but the quantum yield determined in sunlight should be used in the calculation of predicted half-life.

3.5 Second-order rate constants with 'OH in river water

Because \( p\text{CBA} \) was included in the river water experiments, competition kinetics can be used to determine the second order rate constant with 'OH to test for any effect of the matrix or light source by comparing the results to those measured with \( \text{H}_2\text{O}_2 \). Fig. 5 shows the competitive oxidation of the QACs by 'OH in MRW under simulated and natural sunlight corrected for losses not due to indirect photolysis. As with the 'OH sensitizer experiments, BZT, \( \text{C}_{12}\text{BAC} \), and \( \text{C}_{14}\text{BAC} \) react with 'OH in the river water at or near diffusion controlled rates. Association with dissolved organic matter did not significantly influence the photochemical transformation rates of QACs with 'OH based on the similarity of the values (within 10%) to those determined using \( \text{H}_2\text{O}_2 \) as a sensitizer.

The outdoor experimental data overlay the indoor results in river water demonstrating that simulated sunlight experiments serve as good proxies for understanding the photochemical behavior of QACs in surface waters with respect to reaction with 'OH. All calculated bimolecular reaction rate constants (Table 1) are within the 95% confidence intervals for the 3 sets of experiments serving as robust validation of the values. Due to the overlap of the indoor and outdoor results, we can be reasonably assured in our assumptions about the outdoor experimental data and that the indirect photolysis estimates are correct. Fig. 5 reaffirms that the photochemical fate of QACs in the environment will be highly dependent on 'OH generation in natural waters.

3.6 Calculated half-lives in surface waters

The relative contributions of indirect and direct photolysis were evaluated by comparison of pseudo-first-order rate constants from experiments with river and ultrapure water under simulated and natural sunlight. For most of the QACs studied, direct photolysis under environmental conditions is either slow or nonexistent. Only BZT exhibited appreciable direct photochemical degradation. Direct photolysis half-lives for BZT were estimated to be 5.4-5.7 days under simulated sunlight and 20.6 days in natural sunlight using a direct photolysis rate constant calculated using the solar spectra modeled by SMARTS (Fig. S1†). While the reaction between QACs and 'OH is diffusion controlled, QAC degradation via this process will be relatively slow in the environment. The bimolecular reaction rate constants with 'OH were used to estimate half-lives of the tested QACs in sunlit surface waters using eqn (4) and assuming an [OH\(^{\text{is}}\)] of \( 1 \times 10^{-16} \) M on average over 7 hours of daily sunshine.63 Maximum near-surface steady-state 'OH concentrations range from 10\(^{-17}\) to 10\(^{-15}\) M in sunlit surface waters depending on the concentrations of photoproducing and scavenging species, latitude, and time of year.54,73,74 The half-lives of QACs in the photic zone presented in Table 2 reflect a lower bound (minimum persistence) because they are estimated based on conditions in which average maximum rates of 'OH photoproduction occur in the photic zone of a water body at midday during the summertime.

\[
\text{t}_{1/2} = \frac{\ln(2)}{k_{\text{OH, QAC}} \times [\text{OH}^{\text{is}}]} \tag{4}
\]

Because BZT is susceptible to both indirect and direct photolysis under relevant environmental conditions, the half-life of BZT in river water is estimated by extrapolating the experimental results for BZT and using the overall pseudo-first-order rate constant for photolytic loss (eqn (5)), where \( k_i \) (ESI S3 eqn (1)†) is the direct photolysis pseudo-first-order rate constant of BZT in river water under natural sunlight.

Fig. 5 log-concentrations of QACs versus para-chlorobenzoic acid from solar simulator (solid symbols) and natural sunlight (open symbols) irradiation experiments in MRW. QAC concentrations are corrected to only reflect indirect photochemical loss due to 'OH. Solid and dashed lines represent linear regressions for solar simulator and natural sunlight experiments, respectively.
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Table 2 Estimated QAC half-lives in surface water in H$_2$O$_2$ sensitizer, simulated sunlight (indoor) river water, and natural sunlight (outdoor) river water experiments.$^{a,b}$

<table>
<thead>
<tr>
<th>QAC</th>
<th>$t_{1/2}$ (days) H$_2$O$_2$</th>
<th>$t_{1/2}$ (days)$^c$ river water indoor</th>
<th>$t_{1/2}$ (days)$^c$ river water outdoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_{12}$-BAC</td>
<td>26 ± 2</td>
<td>24 ± 4</td>
<td>24 ± 2</td>
</tr>
<tr>
<td>C$_{14}$-BAC</td>
<td>23 ± 3</td>
<td>24 ± 5</td>
<td>23 ± 6</td>
</tr>
<tr>
<td>BZT</td>
<td>26 ± 1</td>
<td>12 ± 1</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>ATMA</td>
<td>27 ± 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DADMA</td>
<td>94 ± 32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{a}$ Errors represent 95% confidence intervals. $^b$ Calculated assuming 7 hours of sunshine per day. $^c$ BZT $t_{1/2}$ including direct photolysis + O$_2$.

$$k_{obs,BZT} = k_{OH,BZT} \times [\text{OH}]_{ss} + k_c \quad (5)$$

While QACs demonstrate shorter lifetimes compared to ionic liquid cations,$^{66}$ they still have half-lives on the order of weeks to months, highlighting their slow photochemical transformation in rivers and lakes, and their persistence in the aquatic environment. The results and half-life estimates were consistent for outdoor and indoor river water photolysis experiments as well as for H$_2$O$_2$ sensitizer experiments, reiterating the importance of OH over other PPRIs in the fate of QACs in surface waters.

4. Conclusions

The current study elucidates the photochemical fate of QACs in surface waters. For most of the QACs evaluated, indirect photolysis is more important than direct photolysis under simulated and natural sunlight. Through model sensitizer and quencher experiments, it is clear that all QACs studied will react predominantly with OH produced in natural waters despite variations in structure, such as side-chain length and presence of aromatic rings. In waters with low steady-state OH concentrations and deeper in the water column, the rates of reaction between QACs and OH will be substantially slower and thus QAC lifetimes will be longer. The results of this study contribute to a more holistic and systematic evaluation of the fate of QACs in near-surface waters as well as the potential for their attenuation in the environment. Reported half-lives and rate constants can be used in future models to predict the fate of QACs in the environment, which could inform risk assessments and regulatory decisions on biocide usage given the growing public health concern over the proliferation of antibiotic resistant bacteria in the environment. Additionally, the hydroxyl radical reaction data could be applied to assessing the removal of QACs during advanced oxidation treatment.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We would like to acknowledge Dr Sarah Pati for help with LC-MS/MS measurements as well as Makenzie Pillsbury. Mass spectrometry was carried out in the Analytical Biochemistry Shared Resources of the Masonic Cancer Center, University of Minnesota, funded in part by Cancer Center Support Grant CA-77598. The authors thank Annika Heaps and Bryanna Lopez-Moran for assistance with laboratory work. This work was funded by the Minnesota Environmental and Natural Resources Trust fund (M.L. 2017, Chp. 96, Sec. 2, Subd. 04a) as recommended by the Legislative and Citizen Commission on Minnesota Resources.

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