1,3,5-Trimethoxybenzene (TMB) as a new quencher for preserving redox-labile disinfection byproducts and for quantifying free chlorine and free bromine

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Abstract

Sodium sulfite, sodium thiosulfate, and ascorbic acid are commonly used to quench free chlorine and free bromine in studies of disinfection byproducts (DBPs) in drinking water, wastewater, and recreational water. The reducing capabilities of these quenchers, however, can lead to the degradation of some redox-labile analytes. Ammonium chloride, another common quencher, converts free chlorine into monochloramine and is therefore inappropriate for analytes susceptible to chloramination. Herein, we demonstrate the utility of 1,3,5-trimethoxybenzene (TMB) as a quencher of free chlorine and free bromine. The reactivity of TMB toward free chlorine was characterized previously. The reactivity of TMB toward free bromine was quantified herein ($k_{\mathrm{HOBr,TMB}} = 3.35\times10^{6}$ M^{-1} s^{-1}) using competition kinetics. To explore the feasibility of TMB serving as a free halogen quencher for kinetic experiments, chlorination of 2,4-dichlorophenol, bromination of anisole, and chlorination and bromination of dimethenamid-P were examined. Although TMB does not react with free chlorine or free bromine as quickly as do some (but not all) traditional quenchers, there was generally no significant difference in the experimental rate constants with TMB (relative to thiosulfate) as the quencher. By monitoring the chlorination and bromination products of TMB, free halogen residuals in quenched samples were quantified. Furthermore, TMB did not affect the stabilities of DBPs (e.g., chloropicrin and bromoacetonitriles) that otherwise degraded in the presence of traditional quenchers. TMB could, therefore, be an appropriate quencher of free chlorine and free bromine in aqueous halogenation experiments involving redox-labile analytes and/or when selective quantification of residual free halogens is desired.

1. Introduction

Quenching residual oxidants is indispensable for identifying and quantifying disinfection byproducts (DBPs), which can be produced when water is treated with a chemical disinfectant (e.g., free chlorine or another oxidant). Various methods exist for quenching free chlorine, which is the most widely used disinfectant for drinking water treatment in the United States.[1] When choosing an appropriate quencher, previous researchers usually sought the following characteristics: "(1) rapid and complete reaction with residual oxidants; (2) chemical inertness towards the analytes; (3) negligible effects on quantitation; and (4) undetectable signal (for itself or its reaction products)."[2] The first three characteristics are especially important for researchers who wish to determine the kinetics of DBP (trans)formation. The fourth characteristic is considered desirable because a quencher that cannot be detected by the analytical instrument employed would not be expected to interfere with analyte signals.

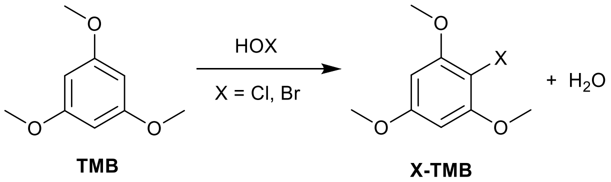
Reagents that are commonly used to quench free chlorine can be divided into two major categories. Quenchers in the first major category reduce free chlorine (Cl(+I) or Cl(0)) to chloride (Cl^-).[3] Examples of such quenchers are sodium thiosulfate ($Na_2S_2O_3$), sodium sulfite (Na_2SO_3), and ascorbic acid. The high redox reactivities of these compounds toward free chlorine result in rapid quenching; the downside is that these compounds can transform analytes that are redox active. Na_2SO_3, for instance, can dehalogenate chloropicrin, trichloroacetonitrile, and dibromoacetonitrile.[4, 5] $Na_2S_2O_3$ can reduce *N*-acetyl-*p*-benzoquinone imine and 1,4-benzoquinone to acetaminophen and 1,4-hydroquinone, respectively.[6] Ascorbic acid can convert the chlorination product of the antiretroviral drug nevirapine back into the parent compound.[7] Moreover, Na_2SO_3, $Na_2S_2O_3$, and ascorbic acid can reduce *N*-chloro-2,2-dichloroacetamide to

2,2-dichloroacetamide, possibly leading to erroneous identification of the latter as a drinking water DBP.[8]

Quenchers in the second major category react with free chlorine to form monochloramine (NH_2Cl), which generally reacts with organic compounds more slowly than does free chlorine.[3] Ammonium chloride (NH_4Cl) is the most commonly encountered quencher in this category; it is considered to be a “soft” quencher since it does not reduce/transform redox-labile N-chlorinated products of organic compounds such as sulfamethoxazole[9] and tramadol.[10] Nonetheless, some organic compounds (e.g., phenols) can react with NH_2Cl.[11] Although chloramination reactions tend to be slower than chlorination reactions,[3] using NH_4Cl to quench free chlorine may affect the quantitation of analytes if the sample storage time is prolonged. NH_4Cl may be particularly problematic for water samples that contain free bromine (e.g., HOBr) because bromamines are relatively potent brominating agents for organic compounds.[12, 13]

An additional (and largely unexplored) category of quenchers comprises organic compounds that are susceptible to electrophilic substitution involving free chlorine and free bromine. In addition to quenching, such organic compounds can facilitate quantitation of residual free chlorine and free bromine provided that the products resulting from electrophilic substitution are stable. For example, Shah et al.[14, 15] employed phenolic compounds (e.g., phenol and 2,6-dichlorophenol) as quenchers of free halogens. Using phenolic compounds can, however, be complicated by the formation of multiple halogenated products (particularly with phenol) and by precipitation of the added quencher (as observed for 2,6-dichlorophenol[15]).

We propose that 1,3,5-trimethoxybenzene (TMB) could serve as an effective quencher of free chlorine and free bromine without the limitations of traditional quenchers—namely, the impact of traditional quenchers on DBP stability. TMB reacts with free chlorine to form a chlorinated product (**Scheme 1**) that can be readily analyzed via gas chromatography-mass spectrometry (GC-MS). As such, when present in sufficient excess, TMB can both quench free chlorine and concurrently generate a single, stable product (2-chloro-1,3,5-trimethoxybenzene, Cl-TMB).[16] When free bromine is present, as in the case of chlorinating waters containing bromide, TMB also reacts with free bromine to form a single, stable product (2-bromo-1,3,5-trimethoxybenzene, Br-TMB).[17] Quantifying the monohalogenated products of TMB could, therefore, allow researchers to selectively determine the concentrations of free chlorine and free bromine in aqueous solutions. TMB, Cl-TMB, and Br-TMB are all commercially available.



Scheme 1. Reactions of free chlorine and free bromine with excess 1,3,5-trimethoxybenzene (TMB) form monochlorinated and monobrominated products (X-TMB).

The presence of three methoxy groups, which activate aromatic systems toward electrophilic substitution,[18] suggests that TMB will undergo facile reactions with free chlorine and free bromine. Whether TMB is sufficiently reactive to serve as a satisfactory quencher can be estimated using the ratio (Q) of the quenching rate to the rate of a reference reaction of interest (e.g., halogenation of a model compound) determined using a traditional quencher:

$$Q = \frac{\text{rate of quenching}}{\text{rate of reference reaction}} = \frac{k_{\text{app,quench}}\,[\text{free halogen}]\,[\text{quencher}]}{k_{\text{app,ref}}\,[\text{free halogen}]\,[\text{model}]} = \frac{k_{\text{app,quench}}\,[\text{quencher}]}{k_{\text{app,ref}}\,[\text{model}]} \quad (1)$$

where $k_{\text{app,quench}}$ and $k_{\text{app,ref}}$ are apparent second-order rate constants ($M^{-1}\ s^{-1}$) for free halogen quenching and for the reference reaction, respectively; [free halogen] represents the molar concentration of free chlorine or free bromine; [quencher] denotes the molar concentration of the quencher of interest; [model] denotes the molar concentration of the model compound of interest in the reference reaction. When Q is large (i.e., ≥100) and the quencher is added in excess of the total free halogen concentration, quenching time (i.e., the time needed for complete consumption of free halogens) is unlikely to appreciably influence measured rates (and the associated rate constants) of reference reactions.

Second-order rate constants for reaction of TMB with free chlorine species (HOCl, Cl_2, Cl_2O) have been reported[16] and can be used to estimate $k_{\mathrm{app,quench}}$ under hypothetical solution conditions. For example, at pH 7.0 and 20 °C in the presence of free chlorine (28 μM ≈ 2 mg/L as Cl_2) and chloride (0.3 mM ≈ 11 mg/L), $k_{\mathrm{app,quench}} \approx 600\ \mathrm{M^{-1}\ s^{-1}}$. Accordingly, if [quencher]/[model] = 5, TMB is anticipated to serve as a satisfactory quencher (Q = 100) of free chlorine for reference reactions for which $k_{\mathrm{app,ref}} \leq 30\ \mathrm{M^{-1}\ s^{-1}}$, which likely applies to chlorination of a range of organic compounds (e.g., various phenols, anisoles, and amides, among others).[19] Working at [quencher]/[model] > 5 could conceivably expand the utility of TMB-quenching to include reference reactions in even more reactive systems. As rate constants characterizing the inherent reactivity of TMB toward free bromine have not been previously reported, a similar analysis for the use of TMB to quench free bromine is currently not feasible. Thus, we opted to determine rate constants for TMB bromination in this study.

The objective of this work was to evaluate TMB as a quencher of free chlorine and free bromine in aqueous halogenation experiments. The stoichiometry was determined for reactions involving TMB and free chlorine/bromine. The inherent reactivity of TMB toward free bromine was also quantified. Rate constants for the chlorination and/or bromination of three model compounds (2,4-dichlorophenol, anisole, and the herbicide dimethenamid-P) were determined with TMB as the free halogen quencher and compared to values obtained using $Na_2S_2O_3$ as the quencher. We chose to examine these halogenation reactions because their rate constants have previously been reported in the literature.[20-23] Unreacted TMB and its monohalogenated products were also analyzed in selected samples to quantify residual free chlorine and free bromine at the time of quenching.

To determine whether TMB would be a useful quencher in studies involving DBPs, the stabilities of chloropicrin, chloral hydrate, tribromoacetaldehyde, and four haloacetonitriles in the presence of TMB were assessed in batch reactors over 7 days. Furthermore, the rate at which TMB quenches chlorine relative to four traditional quenchers was determined in a series of competitive quenching experiments. The reactivity of TMB with monochloramine was also assessed in a batch reactor. Findings from this work could expand the choice of free halogen quenchers for future DBP studies and related experiments involving redox-labile analytes.

2. Experimental

All aqueous solutions were prepared using deionized water further purified with a Nanopure Analytical UV system (Thermo Scientific) or distilled water purified with a Milli-Q Advantage A10 system (EMD Millipore) to a resistivity ≥18 MΩ cm. Laboratory-grade sodium hypochlorite (NaOCl, ~6% w/w, Fisher Scientific) served as the source of free chlorine and was standardized via iodometric titration.[24] Working solutions of free chlorine were prepared daily by diluting the NaOCl stock solution with water and were standardized via UV-vis spectrophotometry.[25] Additional reagents are described in **Table S1** of the Electronic Supplementary Information (ESI). Procedures for synthesizing 2,4-dichloro-1,3,5-trimethoxybenzene and 2,4-dibromo-1,3,5-trimethoxybenzene are provided in the ESI. Procedures for synthesizing 2-bromo-4-chloro-1,3,5-trimethoxybenzene, chloro-dimethenamid-

P, and bromo-dimethenamid-P, as well as the NMR spectra associated with these compounds (**Fig. S1 – S6**), are in the ESI. The NMR data for dimethenamid-P are also included in the ESI (**Fig. S7 – S8**).

2.1 Stoichiometry of TMB reactions with free chlorine and free bromine. The ability of TMB to react stoichiometrically with free chlorine and free bromine to give halogenated products was investigated via halogenation reactions performed at room temperature (21 ± 1 °C) and at varying $[HOCl]_{tot,o}$ and $[HOBr]_{tot,o}$, respectively. For the chlorination of TMB, reaction solution (total volume = 25 mL) containing borate buffer (20 mM, adjusted to pH 8.00 using HNO_3) and $NaNO_3$ (0.1 M) was placed in 40-mL amber glass vials. NaOCl was then added to the reaction solution ($[NaOCl]_o$ in reactor = 5.0–46 μM), and the vials were capped and shaken vigorously for 10 s. For the bromination of TMB, reaction solution (total volume = 25 mL) containing borate buffer (20 mM, adjusted to pH 8.00 using HNO_3), $NaNO_3$ (0.1 M), and NaBr (5.0–60 μM) was placed in 40-mL amber glass vials. NaOCl was then added to the reaction solution ($[NaOCl]_o$ in reactor = 65 μM). Following NaOCl addition, reactors were capped, shaken vigorously for 10 s, and allowed to stand for 5 min to permit bromide oxidation by excess free chlorine.

For all experiments, three aliquots (1.00 mL each) of the reaction solution were obtained from each reactor and transferred to individual 4-mL amber glass vials pre-amended with TMB (0.150 mL at 2.76 mM, dissolved in methanol). Chlorination and bromination of primary alcohols are generally slow,[19, 26] so the presence of methanol is not anticipated to interfere with the reaction of TMB with free halogens. Molar ratios of [TMB]-to-[free chlorine] ranged from 8:1 to 72:1; molar ratios of [TMB]-to-[free bromine] ranged from 6:1 to 72:1. The 4-mL vials were capped and shaken manually for 10 s and allowed to stand for 5 min. After all samples were quenched with TMB, toluene (1.00 mL, containing 2-chlorobenzonitrile at 10.2 μM as the internal standard) was added to each 4-mL vial as the extraction solvent. Vials were capped and shaken manually for 30 s. An aliquot of the toluene phase (0.20 mL) was transferred to a 0.3-mL glass insert seated inside an amber glass 2-mL autosampler vial. These vials were capped with a screw-top plastic cap fitted with a PTFE-lined septum. The concentrations of TMB, Cl-TMB, and Br-TMB in the toluene samples were determined using GC-MS (see ESI, **Table S2**, for method details for analysis of TMB and its monohalogenated products; **Table S2** also contains method details for analysis of anisole and its bromination products, which will be discussed further in Section 2.3).

2.2 TMB as a quencher of free chlorine: Chlorination of 2,4-dichlorophenol. The effectiveness of TMB in quenching free chlorine was assessed by determining rate constants for the chlorination of 2,4-dichlorophenol (2,4-DCP) at pH 7.08 and 9.14 using either TMB or sodium thiosulfate as the quencher. At each pH, two identical reactors (40-mL amber glass vials) were set up with 31 mL of reaction solution in each. The reaction solution consisted of phosphate buffer (10 mM, adjusted to pH 7.08 using NaOH) or carbonate buffer (10 mM, adjusted to pH 9.14 using NaOH), NaCl (5 mM), $NaNO_3$ (95 mM), and NaOCl (128 μM). The reactors were kept in the dark inside a stainless-steel constant-temperature water bath set at 25.00 ± 0.01°C for ~8 min to permit temperature equilibration. Previous work in our laboratory showed that free chlorine decay in the absence of 2,4-DCP was negligible at this timescale.[20] To initiate reactions, each vial was spiked with 0.30 mL of 2,4-DCP solution (219 μM in water) using a glass syringe to yield an initial concentration of 2.1 μM. The vial was then capped, shaken vigorously for 5 s, and returned to the water bath. At each sampling time, 2.0 mL of the reaction solution was transferred to a 4-mL amber glass vial pre-amended with 0.20 mL of either TMB (2.77 mM in 50 vol% water and 50 vol% methanol) or $Na_2S_2O_3$ (2.77 mM in water). Sampling times were chosen such that the disappearance of 2,4-DCP was monitored over 3 half-lives. For the experiment conducted at pH 9.14, the TMB spiking solution contained 0.1 M HNO_3 so as to lower the solution pH to ≤ 7 once reactor aliquots were added to the vials (because the chlorination rate of TMB decreases as the pH increases[16]). In all quenched samples, $[\text{quencher}]_o/[\text{NaOCl}]_o \geq 2.2$.

Liquid-liquid extractions were carried out after all samples were quenched. Toluene (0.80 mL with 2-chlorobenzonitrile at 97.6 μM as the internal standard) served as the extraction solvent and was added to each quenched sample. The 4-mL vials were then capped and shaken manually for 10 s. After waiting ≥ 3 min for phase separation to re-establish, a portion of the toluene phase (~ 0.5 mL) was transferred to a 2-mL amber glass autosampler vial and analyzed using GC-MS. Details of the analytical method for 2,4-DCP, TMB, and their chlorinated products are in the ESI (**Table S3**).

2.3 TMB as a quencher of free bromine: Bromination of anisole. The performance of TMB as a quencher for kinetic experiments involving bromination of anisole was examined via batch reactors. In order to facilitate a comparison of quenchers, the experimental setup was the same as that described in a previous study[22] in which $Na_2S_2O_3$ was used to quench free halogens. Briefly, reaction solutions (total volume = 25 mL) were prepared in 40-mL amber glass vials and contained NaBr (130 μM), carbonate buffer (20 mM, adjusted to pH 7.48 using HNO_3) or borate buffer (20 mM, adjusted to pH 8.02, 8.50, or 9.02 using HNO_3), $NaNO_3$ (90 mM), NaCl (10 mM), and anisole (6.0 μM). Reactors were incubated in a circulating water bath at 20.00 ± 0.01 °C for 4 min prior to dosing with NaOCl (305 μM) at t = 0. Following addition of NaOCl, vials were capped, shaken manually for 10 s, and returned to the water bath. Aliquots from the reactors (0.90 mL) were obtained periodically and transferred to 4-mL amber glass vials pre-amended with TMB. To minimize the extent to which monobrominated products of anisole underwent subsequent bromination, sampling times were chosen such that the loss of anisole was monitored over at least 1 but no more than 2 half-lives. For the reaction at pH 7.5, 1.00 mL of TMB solution (938 μM dissolved in 80 vol% water and 20 vol% methanol) was added to each 4-mL glass vial. For reactions at pH ≥ 8.0, 0.210 mL of TMB solution (2.62 mM in methanol) was added to each 4-mL glass vial. The 4-mL vials were capped and shaken manually for 10 s after aliquots from the reactors were added.

Once all samples were quenched, toluene (0.45 mL, containing 2-chlorobenzonitrile at 10.2 μM as the internal standard) was added to each 4-mL vial as the extraction solvent. Vials were capped and shaken manually for 10 s. After phase separation was re-established, a portion of the toluene phase (0.2 mL) from each sample was transferred to a 0.3-mL glass insert seated inside an amber glass 2-mL autosampler vial. Autosampler vials were secured with a screw-top plastic cap fitted with a PTFE-lined septum. Anisole, TMB, as well as their halogenated products were analyzed concurrently via GC-MS. Details of the GC-MS analytical method are provided in the ESI (**Table S2**).

2.4 TMB as a quencher of free chlorine/bromine: Halogenation of dimethenamid-P.

Similar approaches as described above in Section 2.3 were used to evaluate the efficacy of TMB as a quencher for reactions of dimethenamid-P with free chlorine and free bromine. Reactors with solutions containing NaBr (4.5 μM in chlorination experiments or 130 μM in bromination experiments), borate buffer (10 mM, adjusted to pH 8.00 using HNO_3), $NaNO_3$ (98.6 mM), NaCl (1.3 mM), and dimethenamid-P (10 μM) were incubated in a circulating water bath kept at 20.00 ± 0.01 °C. NaOCl (305 μM) was added to the reactors at t = 0. A prior chlorination study[23] demonstrated the ability of trace bromide present in ostensibly bromide-free salts (e.g., NaCl) to affect transformation rates of dimethenamid. The low level of added NaBr in the dimethenamid-P chlorination experiments herein attenuated the uncertainty in the bromide concentrations without interfering with quantitation of dimethenamid-P chlorination rates. Aliquots from batch reactors were quenched using TMB or $Na_2S_2O_3$ ($[TMB]_o$ = 500 µM and $[Na_2S_2O_3]$ = 450 µM at the time of quenching). Quenched aliquots were extracted into toluene. Toluene extracts were analyzed via GC-MS for dimethenamid-P, TMB, and their halogenated products. Additional methodological details for experiments involving dimethenamid-P are available in the ESI (**Table S4**).

The experimental designs described in Sections 2.2 – 2.4 (chlorination of 2,4-DCP, bromination of anisole, and halogenation of dimethenamid-P, respectively) are consistent with the general approach of several previous kinetics studies of organic compound halogenation,[16, 20-23, 27] except that these prior studies employed $Na_2S_2O_3$ rather than TMB as a quencher. Solution conditions (e.g., temperature, pH range, and ionic strength) employed herein were selected to permit comparisons to prior studies.[20-23]

2.5 Competitive quenching of free chlorine. The rate at which TMB reacts with free chlorine relative to four traditional quenchers (Na_2SO_3, $Na_2S_2O_3$, ascorbic acid, and NH_4Cl) was assessed via competitive quenching experiments. Each reactor (60-mL clear glass vials wrapped in aluminum foil) contained 50 mL of reaction solution, which consisted of phosphate buffer (10 mM, adjusted to pH 7.10 with NaOH), $NaNO_3$ (0.1 M), and NaOCl (52 µM). The reactors were kept in the dark inside a stainless-steel constant-temperature water bath set at 25.00 ± 0.01°C. After waiting ~8 min for the reaction solution to achieve temperature equilibration, each reactor was spiked with 0.50 mL of a solution that contained equimolar concentrations of TMB and a non-TMB quencher (nominally 52 μM of each in 50 vol% water and 50 vol% methanol). The reactor was then capped, shaken vigorously, and returned to the water bath. After 5 min, 3.0 mL of the reaction solution from each reactor was transferred to a clear glass 15-mL centrifuge tube containing 1 mL of toluene (with 2-chlorobenzonitrile at 40.6 μM as the internal standard). The contents of the centrifuge tubes were mixed vigorously using a vortex mixer for 2 minutes. An aliquot of the toluene phase (0.5 mL) was transferred to a 2-mL amber glass autosampler vial. The concentrations of TMB and its monochlorinated product in the toluene extract were analyzed using GC-MS (see ESI for method details, **Table S3**).

2.6 Determining the reactivity of TMB toward free bromine. The inherent reactivity of TMB toward free bromine was assessed via competitive halogenation experiments employing dimethenamid-P as a reference compound. Dimethenamid-P was selected as the reference compound because the rate constants associated with its aqueous bromination are known.[21] Reaction solutions (total volume = 25 mL) were prepared in 40-mL amber glass vials and contained borate buffer (20 mM), NaBr (typically 10 μM), $NaNO_3$ (typically 90 mM), NaCl (typically 10 mM), and NaOCl (typically 20 μM). The pH of reaction solutions was adjusted using HNO_3 and/or NaOH. The effects of added NaCl (14 – 37 mM, at pH 7.1), NaBr (15 – 31 μM, at pH = 7.0), and NaOCl (20 – 34 μM, at pH 7.0) on bromination rates of TMB (relative to those of dimethenamid-P) were examined. [NaCl], [NaBr], and [NaOCl] were investigated as independent variables due to their ability to influence bromine speciation and thereby affect bromination rates.[21, 22, 27] To control ionic strength, the amount of added $NaNO_3$ was adjusted such that $[NaNO_3]$ + [NaCl] was uniform (typically at 0.1 M) during experiments examining each aforementioned independent variable. Following addition of NaOCl, vials were capped, shaken manually for 10 s, and incubated in a circulating water bath at 20.00 ± 0.01 °C for at least

5 min to permit oxidation of bromide. At t = 0, a methanolic spiking solution (130 μL) containing TMB (2.1 mM) and dimethenamid-P (21 mM) was added to each 40-mL glass vial. The glass vials were subsequently capped, shaken manually for 10 s, and returned to the water bath. After 1.0 min of reaction time, three aliquots (1.00 mL each) from each reactor were obtained and transferred to individual 4-mL amber glass vials pre-amended with sodium thiosulfate (75 μL at 10 mM) to quench residual chlorine. The 4-mL vials were capped and shaken manually for 10 s.

After samples were quenched, toluene (0.50 mL, containing 2-chlorobenzonitrile at 10.2 μM as the internal standard) was added to each 4-mL vial as the extraction solvent. Vials were capped and shaken manually for 30 s. After phase separation was re-established, a portion of the toluene phase (0.2 mL) from each sample was transferred to a 0.3-mL glass insert seated inside an amber glass 2-mL autosampler vial. Autosampler vials were secured with a screw-top plastic cap fitted with a PTFE-lined septum. Dimethenamid-P, TMB, as well as their halogenated products were analyzed concurrently via GC-MS. Details of the GC-MS analytical method are provided in the ESI (**Tables S4 and S5**). Apparent second-order rate constants for reactions of TMB with free bromine were calculated from the initial and final measured concentrations of TMB and dimethenamid-P based on equations developed in the ESI.

2.7 Influence of quenchers on the stabilities of DBPs. The stabilities of eight DBPs (chloropicrin, chloral hydrate, chloroacetonitrile, dichloroacetonitrile, trichloroacetonitrile, bromoacetonitrile, dibromoacetonitrile, and tribromoacetaldehyde) were assessed individually in the presence of TMB, Na_2SO_3, $Na_2S_2O_3$, ascorbic acid, and NH_4Cl. These DBPs were chosen because authentic standards are commercially available, and their stabilities in the presence of various traditional quenchers have been examined by previous researchers, thus permitting comparisons with results from this study. Na_2SO_3 solutions were made fresh daily as the sulfite oxidized rapidly when headspace was present. Spiking solutions of DBPs were prepared in either methanol (chloropicrin) or acetonitrile (all other DBPs). Each reactor (clear glass bottle with ground-glass stopper, actual volume ≈ 315 mL) contained 300 mL of phosphate buffer (10 mM, adjusted to pH 7.0 using NaOH) and one quencher at an initial concentration of 60 μM. The reactor was then spiked with a DBP to give an initial concentration of 6.0 μM and shaken vigorously. A control reactor, to which no quencher was added, was set up for each DBP to determine whether processes such as volatilization and hydrolysis could affect the stability of the DBP. All reactors were kept in a constant-temperature incubator set at 25 ± 1 °C and were sampled once a day for 7 days. At each sampling time, 4.0 mL of the reaction solution were transferred to a clear glass 15-mL centrifuge tube containing 1.5 mL of methyl *tert*-butyl ether (MTBE, with 1,2-dibromopropane at 10 μM as the internal standard). Although the volume of headspace in the reactor increased over the course of the experiment, the percentage of each DBP in the aqueous solution (calculated using Henry's Law constants obtained from the program HENRYWIN[28]) never dropped below 98%. The introduction of headspace can result in the dissolution of molecular oxygen into reaction solutions. The extent to which sulfite might have reacted with molecular oxygen[29] was not quantified herein. The centrifuge tube was then vortexed for 2 min, and ~1 mL of the MTBE phase was subsequently transferred to a 2-mL amber glass autosampler vial. The concentrations of DBPs in the MTBE extracts were analyzed using GC with micro-electron capture detection (μ-ECD). Additional details of the analytical methods are in the ESI (**Tables S6 – S8**).

2.8 Chloramination of TMB. To assess whether the presence of monochloramine could interfere with the quantification of free chlorine using TMB, a batch reactor was set up to examine the chloramination kinetics of TMB. The reactor (60-mL clear glass vial) contained 50 mL of reaction solution that consisted of phosphate buffer (10 mM, adjusted to pH 7.03 with NaOH) and ammonium chloride (NH_4Cl; 385 μM). The reactor was placed inside a stainless-steel constant-temperature water bath set at 25.00 ± 0.01°C. After several minutes of temperature equilibration, 1 mL of NaOCl (7.86 mM) was added to the reactor, yielding an initial concentration of 154 μM ($[NH_4Cl]_o/[NaOCl]_o = 2.5$). The reactor was capped, shaken vigorously, and returned to the water bath. After waiting ~7 min to permit formation of monochloramine, the reactor was spiked with 0.10 mL of a TMB solution (5.50 mM in methanol) such that $[TMB]_o = 10.8$ μM. The reactor was again capped, shaken vigorously, and returned to the water bath. At each sampling time, 3.0 mL of the reaction solution were transferred to a clear glass 15-mL centrifuge tube containing 1.0 mL of toluene (with 2-chlorobenzonitrile at 40.0 μM as the internal standard). The centrifuge tube was vortexed for 2 min, and ~0.5 mL of the toluene layer was transferred to a 2-mL amber glass autosampler vial. The concentrations of TMB and Cl-TMB in the toluene extracts were quantified using GC-MS. Details of the GC-MS method are in the ESI (**Table S3**).

3. Results and Discussion

Commonly used quenchers of free chlorine and free bromine can potentially reduce/transform analytes of interest in aqueous samples, leading to inaccurate quantitation of the analytes. This sparked our desire to develop an alternative method for quenching free halogens using TMB. In addition, by measuring the concentrations of the monochlorinated and monobrominated products of TMB in quenched samples, residual concentrations of free chlorine and free bromine can be determined. The effectiveness and limitations of using TMB to quench and quantify free halogens are demonstrated and discussed in the following sections.

3.1 TMB as a dual-purpose quencher for kinetic experiments. Solutions of free chlorine or free bromine were quenched with excess TMB ($[TMB]_o/[HOX]_{tot,o} \geq 6$, X = Cl or Br) to evaluate the conversion efficiency of free chlorine and free bromine into Cl-TMB and Br-TMB, respectively. A plot of [Cl-TMB] as a function of total free chlorine dose (**Fig. 1A**) is linear with a slope not significantly different from 1.00 (at the 95% confidence level). An analogous plot of [Br-TMB] as a function of total free bromine concentration (**Fig. 1B**) is also linear with a slope

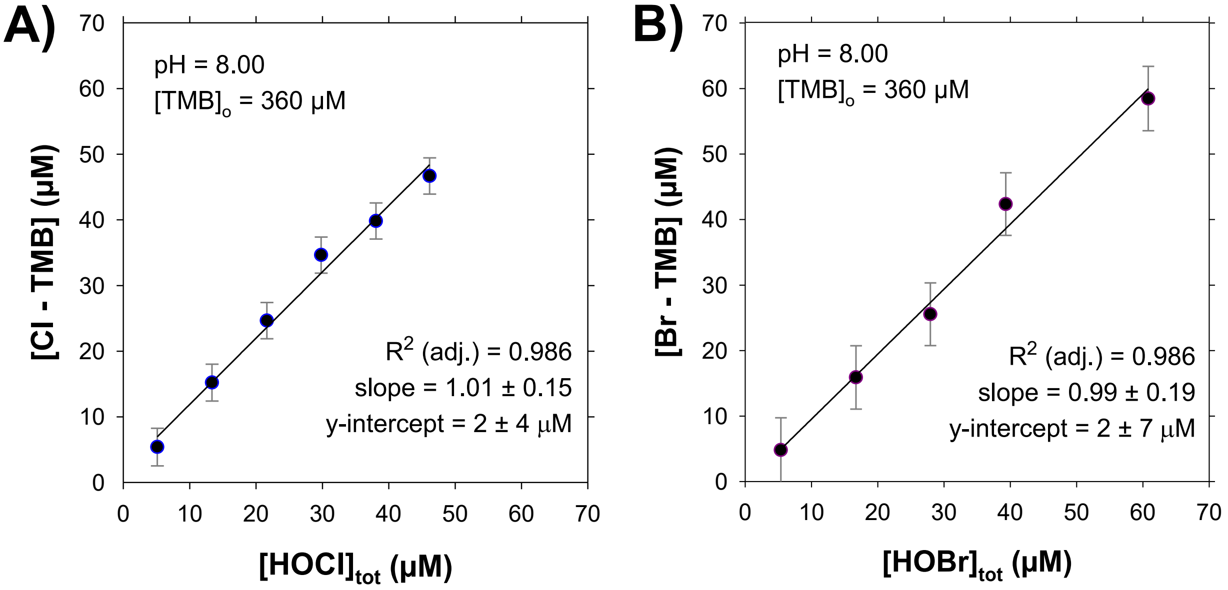


Fig. 1. (A) Yields of 2-chloro-1,3,5-trimethoxybenzene (Cl-TMB) as a function of chlorine dose. Reaction conditions: $[TMB]_o$ = 360 μM, $[NaOCl]_o$ = 5.0–46 μM, $[NaNO_3]$ = 0.1 M, pH = 8.00, $[borate]_{tot}$ = 20 mM, T = 21 ± 1 °C. **(B)** Yields of 2-bromo-1,3,5-trimethoxybenzene (Br-TMB) as a function of free bromine concentration; free bromine was generated via oxidation of bromide by excess free chlorine. Conditions: $[TMB]_o$ = 360 μM, $[NaOCl]_o$ = 65 μM, $[Br^-]$ = 5.0–60 μM, $[NaNO_3]$ = 0.1 M, pH = 8.00, $[borate]_{tot}$ = 20 mM, T = 21 ± 1 °C. Cl-TMB was also detected, but for clarity, concentrations of Cl-TMB are not shown. Data points denote average values of experiments performed in triplicate; error estimates denote 95% confidence intervals.

not significantly different from 1.00 (at the 95% confidence level). These results indicate that, under the examined conditions, TMB reacts stoichiometrically with free chlorine and with free bromine to form the respective monochlorinated and monobrominated products.

3.2 Chlorination of 2,4-dichlorophenol. Chlorination of 2,4-dichlorophenol (2,4-DCP) was carried out at pH 7.08 under pseudo-first-order conditions ($[\mathrm{HOCl}]_{\mathrm{tot}} \approx [\mathrm{HOCl}]_{\mathrm{tot,o}} \gg [\text{2,4-DCP}]_{\mathrm{tot,o}}$) with TMB as the free chlorine quencher. The overall rate of 2,4-DCP chlorination in our experiments can be described by:

$$\frac{d[\text{2,4-DCP}]_{\mathrm{tot}}}{dt} = -k_{\mathrm{obs}}[\text{2,4-DCP}]_{\mathrm{tot}} \qquad (2)$$

where k_{obs} represents the pseudo-first-order rate constant and $[\text{2,4-DCP}]_{\mathrm{tot}}$ denotes the sum of the concentrations of the acid and conjugate base forms of 2,4-DCP ($\mathrm{p}K_{\mathrm{a}} = 7.85$; ref 30). The disappearance of 2,4-DCP was accompanied by the formation of 2,4,6-trichlorophenol (TCP) (**Fig. 2A**; concentrations corrected for the dilution that resulted from adding aliquots of the reaction solution to autosampler vials pre-amended with solutions of TMB). The decrease in the carbon mass balance, calculated as $[\text{2,4-DCP}]_{\mathrm{tot}} + [\mathrm{TCP}]_{\mathrm{tot}}$, can be attributed to the reaction of TCP with free chlorine.[20] The value of k_{obs} was computed from the linear regression of $\ln[\text{2,4-DCP}]_{\mathrm{tot}}$ versus time data (**Fig. S9A**). With TMB as the quencher, $k_{\mathrm{obs}} = 8.5\ (\pm\ 0.4) \times 10^{-3}$ s^{-1} (all uncertainties herein indicate 95% confidence intervals). In a parallel 2,4-DCP chlorination experiment in which sodium thiosulfate was used to quench free chlorine, $k_{\mathrm{obs}} = 8.0$ $(\pm\ 0.3) \times 10^{-3}\ \mathrm{s}^{-1}$ (**Fig. S9B**). The difference between the two k_{obs} values is not significant at the 95% confidence level, showing that under our experimental conditions TMB and sodium thiosulfate are equally effective in quenching free chlorine.

When TMB was used as the quencher, the concentrations of unreacted TMB and Cl-TMB in the quenched samples were also monitored (**Fig. 2B**; concentrations not corrected for dilution). Recoveries of free chlorine, computed as ([Cl-TMB] + [TCP])/$[\text{HOCl}]_{\text{tot,o}}$, remained constant at 96% to 102% with an average of 99% ± 2% (**Fig. 2C**), as expected if pseudo-first-order conditions were maintained throughout the experiment. The amount of free chlorine that was incorporated into TMB—quantified as [Cl-TMB]—was within 5% of $[\text{HOCl}]_{\text{tot,o}}$ ($[\text{HOCl}]_{\text{tot,o}}$ = 116 μM at the time of quenching). Additional products besides TCP likely formed from the chlorination of 2,4-DCP; however, under our reaction conditions in which $[\text{HOCl}]_{\text{tot,o}} \gg [\text{2,4-DCP}]_{\text{o}}$, other reactions that contribute to the loss of 2,4-DCP or its daughter products are not anticipated to consume appreciable amounts of free chlorine.

Recoveries of TMB, computed as ([TMB] + [Cl-TMB])/$[\text{TMB}]_{\text{o}}$, ranged from 100% to 102% with an average of 101% ± 1% (**Fig. 2D**). Approximately all of the TMB mass can be accounted for by considering TMB and Cl-TMB, indicating that the formation of additional chlorinated products of TMB (e.g., dichlorinated and trichlorinated TMB) was negligible. Monitoring 2,4-dichloro-1,3,5-trimethoxybenzene in the quenched samples confirmed that dichlorinated TMB accounted for < 0.1% of the total [TMB] (data not shown).

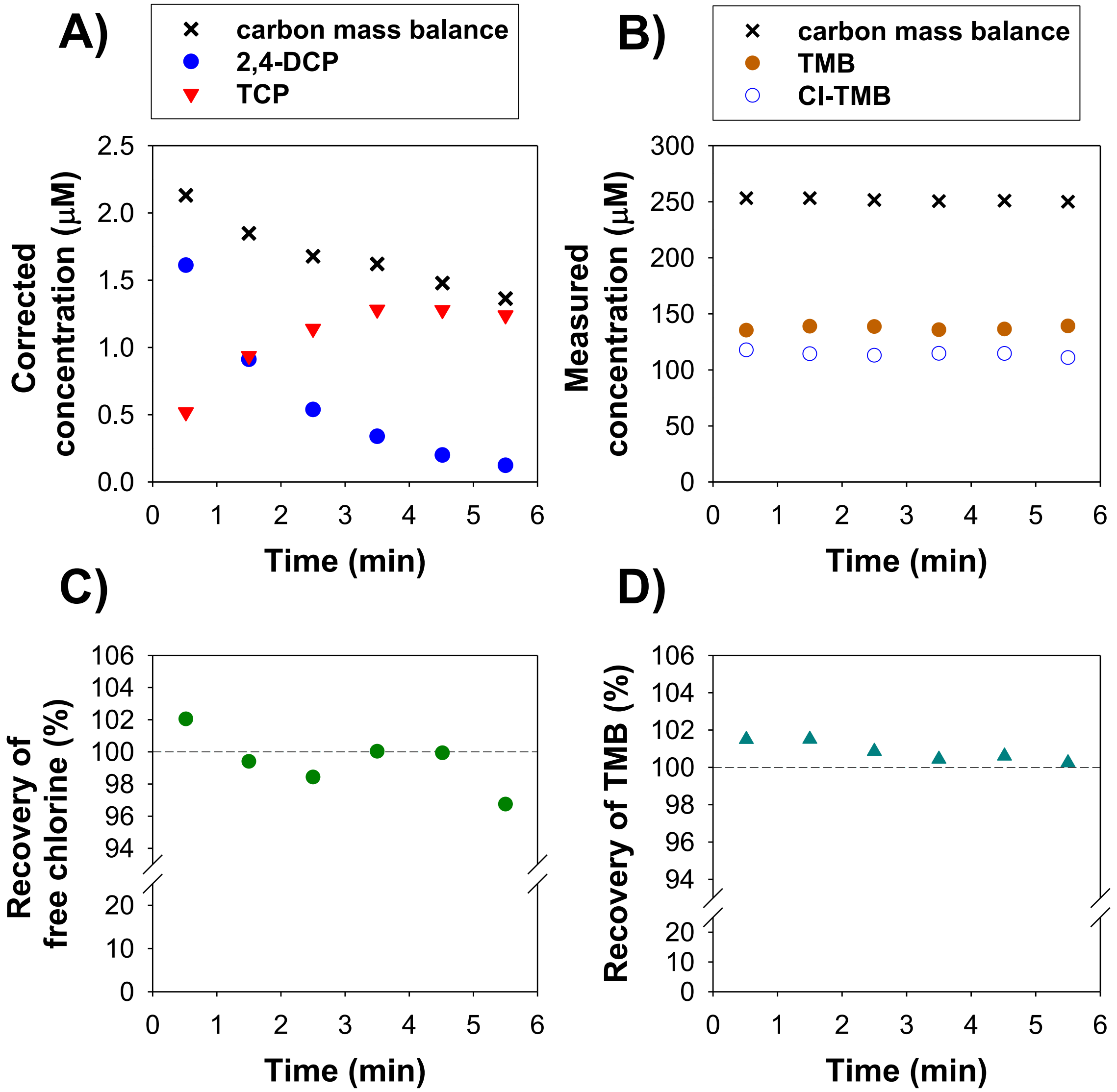


Fig. 2. Reaction of 2,4-DCP with excess free chlorine, quenched using 1,3,5-trimethoxybenzene (TMB). Reaction conditions: pH 7.08, $[2,4\text{-DCP}]_o$ = 2.1 µM, $[NaOCl]_o$ = 128 µM, [phosphate buffer] = 10 mM, $[NaCl]_{added}$ = 5 mM, ionic strength (i.e., [NaCl] + $[NaNO_3]$) = 0.1 M, T = 25.0 °C. **(A)** The concentrations of the parent compound (2,4-DCP) and its chlorination product (TCP) over the course of the experiments. The mass balance was calculated as $[2,4\text{-DCP}]_{tot}$ + $[TCP]_{tot}$ at each time point. **(B)** Measured concentrations of TMB and its major chlorination product, Cl-TMB, over the course of the experiments. The mass balance was calculated as [TMB] + [Cl-TMB] at each time point. **(C)** The recovery of chlorine at each sampling time; % recovery of Cl = ([Cl-TMB] + [TCP])/$[HOCl]_{tot,o}$, where $[HOCl]_{tot,o}$ = 116 µM at the time of quenching. **(D)** The recovery of TMB at each sampling time; % recovery of TMB = ([TMB] + [Cl-TMB])/$[TMB]_o$, where $[TMB]_o$ = 252 µM at the time of quenching.

We also assessed the ability of TMB to quench free chlorine in a 2,4-DCP chlorination experiment conducted at pH 9.14. The quenching was carried out using a TMB solution that contained 0.1 M HNO_3, and the pH of the reactor aliquots after thorough mixing with the TMB solution was between 6 and 7. With TMB as the quencher, $k_{obs} = 6.4\ (\pm 0.2) \times 10^{-4}\ s^{-1}$. In a parallel experiment with sodium thiosulfate as the quencher, $k_{obs} = 6.1\ (\pm 0.3) \times 10^{-4}\ s^{-1}$. The close agreement between the k_{obs} values indicates that TMB can be an effective quencher of free chlorine in high pH solutions when steps are taken to lower the solution pH to ~~≤7~~ 6–7 at the time of quenching, noting that TMB chlorination rates increase with decreasing pH.[16] Accordingly, TMB is anticipated to be effective in quenching free chlorine as long as the sample pH at the time of quenching is modestly acidic.

3.3 Bromination of anisole. TMB was employed as a quencher in kinetic experiments involving bromination of anisole by free bromine (generated via NaBr + excess NaOCl) at pH 7.48. As the bromination of anisole is much more rapid than the analogous chlorination reaction, only brominated products were observed under the time scales of our experiments (**Fig. 3A**). Concentrations of TMB, Cl-TMB, and Br-TMB were measured in the toluene extract obtained at each sampling time (**Fig. 3B**). Recoveries of free chlorine and free bromine ranged from 97 – 104% with averages of 100% ± 3% and 103% ± 2%, respectively (**Fig. 3C**). These results suggest that TMB was converted quantitatively into Cl-TMB and Br-TMB upon reaction with residual free chlorine and free bromine, respectively. Recoveries of TMB ranged from 97% to 100% (average = 99% ± 1%; **Fig. 3D**), which suggests that formation of additional products (e.g., dihalogenated forms of TMB) was negligible.

Under pseudo-first-order conditions in which $[HOBr]_{tot} \approx [HOBr]_{tot,o} \gg [anisole]_o$, the overall rate of anisole bromination can be expressed as:

$$\frac{d[\text{anisole}]}{dt} = -k_{\text{obs}}[\text{anisole}] = -(k_{\text{I,obs}} + k_{\text{II,obs}})[\text{anisole}] \quad (3)$$

where k_{obs}, $k_{\text{I,obs}}$, and $k_{\text{II,obs}}$ are the pseudo-first-order rate constants for the disappearance of anisole, the formation of 4-bromoanisole, and the formation of 2-bromoanisole, respectively. In **Table S9**, values of $k_{\text{I,obs}}$ and $k_{\text{II,obs}}$ determined using TMB as a quencher (at pH 7.48, 8.02, 8.50, and 9.02) are compared to the corresponding values estimated from a previously-reported reactivity model[22] (**eqn 4**) developed from kinetic experiments employing thiosulfate as the quencher:

$$k_{\text{obs}} = k_{\text{BrCl}}[\text{BrCl}] + k_{\text{BrOCl}}[\text{BrOCl}] + k_{\text{Br}_2\text{O}}[\text{Br}_2\text{O}] + k_{\text{HOBr}}[\text{HOBr}] \quad (4)$$

where k_{BrCl}, k_{BrOCl}, $k_{\text{Br}_2\text{O}}$, and k_{HOBr} denote second-order rate constants (M^{-1} s^{-1}) for bromination by BrCl, BrOCl, Br_2O, and HOBr. Molar concentrations of various brominating

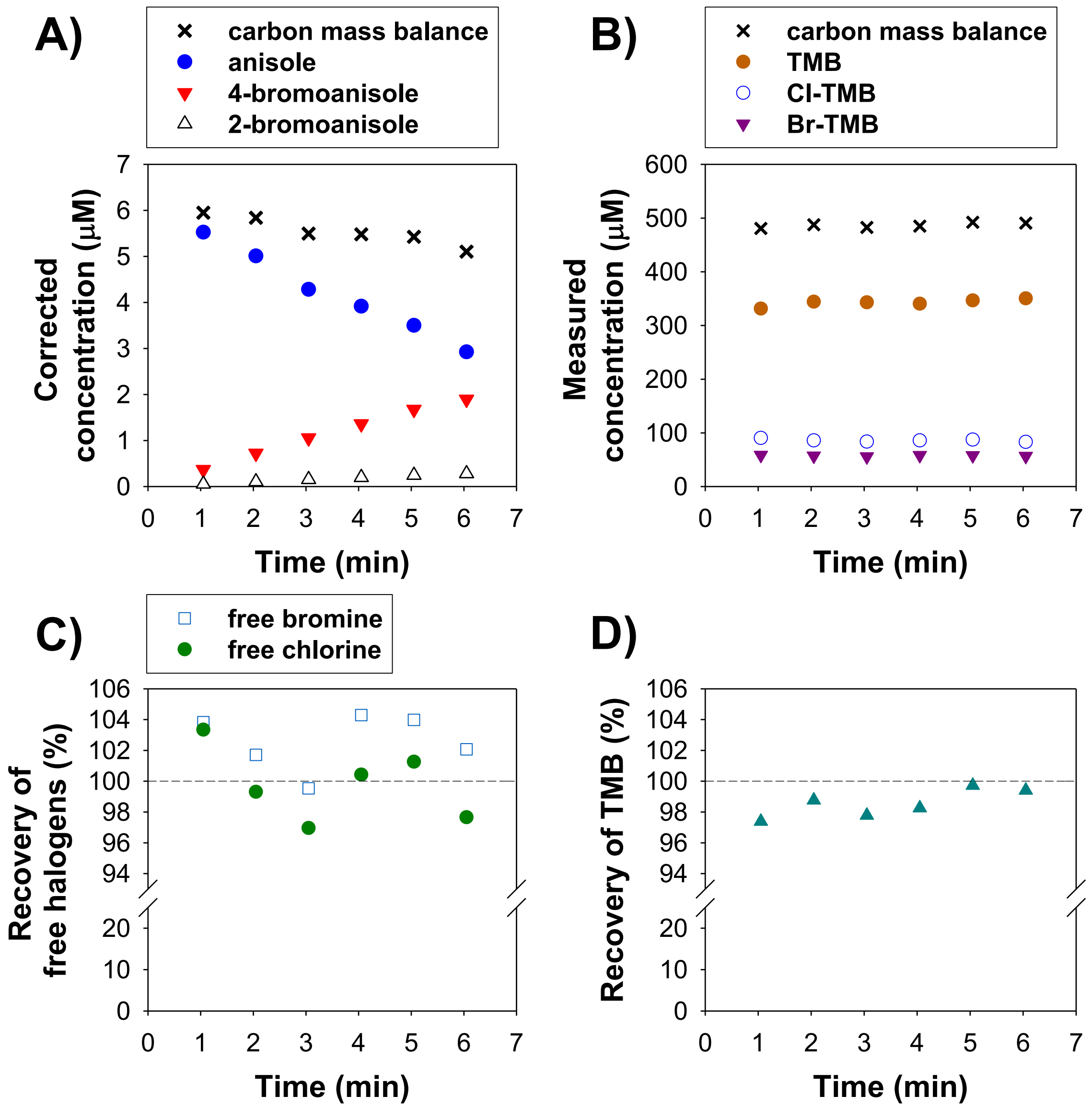


Fig. 3. Reaction of anisole with solutions amended with bromide + excess NaOCl, periodically quenched using 1,3,5-trimethoxybenzene (TMB). Conditions: $[\text{anisole}]_o = 6.0\ \mu M$, $[\text{NaBr}]_o = 130\ \mu M$, $[\text{NaOCl}]_o = 305\ \mu M$, pH = 7.48, [carbonate buffer] = 20 mM, $[\text{NaNO}_3] = 90$ mM, [NaCl] = 10 mM, T = 20.0 °C. **(A)** Time course depicting anisole transformation into brominated products; carbon mass balance = [anisole] + [4-bromoanisole] + [2-bromoanisole]; chlorination of anisole was sufficiently slow as to preclude detection of chlorinated products. Slight decreases observed for the carbon mass balance may be due to formation of dibrominated products, which were not quantified. Concentrations were corrected for the dilution that occurred when adding aliquots of the reaction solution to autosampler vials pre-amended with TMB. **(B)** Measured concentrations (not corrected for dilution) of the quencher (TMB) and its monochlorinated (Cl-TMB) and monobrominated (Br-TMB) products; carbon mass balance = [TMB] + [Cl-TMB] + [Br-TMB]. **(C)** Recovery of free chlorine and free bromine for each sampling time; recovery of chlorine = $[\text{Cl-TMB}]/[\text{HOCl}]_{\text{tot,o}}$, where $[\text{HOCl}]_{\text{tot,o}} = 83\ \mu M$ at the time of quenching; recovery of bromine = $([\text{4-bromoanisole}] + [\text{2-bromoanisole}] + [\text{Br-TMB}])/[\text{Br}^-]_o$, where $[\text{HOBr}]_{\text{tot,o}} = 62\ \mu M$. **(D)** Recovery of TMB = $([\text{TMB}] + [\text{Cl-TMB}] + [\text{Br-TMB}])/[\text{TMB}]_o$, where $[\text{TMB}]_o = 494\ \mu M$ at the time of quenching.

agents were determined using the solution conditions reported in **Table S9** and the equilibrium constants compiled in ref 22. Of the eight rate constants obtained using TMB as the quencher, seven were not significantly different (at the 95% confidence level) from those calculated via **eqn 4** (based on data obtained using sodium thiosulfate as the quencher). In all cases, rate constants obtained using TMB as a quencher differ by ≤ 23% relative to values calculated via **eqn 4** (**Table S9**).

3.4 Chlorination and bromination of dimethenamid-P. To further evaluate the performance of TMB as a quencher relative to sodium thiosulfate, time course experiments involving chlorination and bromination of dimethenamid-P were performed in triplicate at pH 8.00 (**Table 1**). The average pseudo-first-order chlorination rate constant calculated from experiments quenched with TMB differed from that obtained using sodium thiosulfate by 0.4%. The average pseudo-first-order bromination rate constant determined from experiments quenched with TMB differed by –1.6% relative to that obtained using sodium thiosulfate. The aforementioned

Table 1. Pseudo-First-Order Rate Constants for the Formation of Chloro-Dimethenamid-P and Bromo-Dimethenamid-P in Solutions of Free Chlorine + Bromide Measured Using TMB or Sodium Thiosulfate as Quenchers [a]

Product	**Pseudo-first-order rate constant (s^{-1})**		**Percent Difference [b]**	**Significantly Different at 95% CI?**
	Quencher = TMB	**Quencher = Thiosulfate**		
chloro-dimethenamid-P	$(6.6 \pm 0.7) \times 10^{-5}$	$(6.6 \pm 0.5) \times 10^{-5}$	0.4%	No
bromo-dimethenamid-P	$(3.2 \pm 0.2) \times 10^{-2}$	$(3.3 \pm 0.2) \times 10^{-2}$	–1.6%	No

[a] Rate constants denote averages of triplicate experiments. Uncertainties represent 95% confidence intervals. Reaction conditions: pH = 8.00, [borate buffer] = 10 mM, [dimethenamid-P]$_o$ = 10 µM, [NaOCl]$_o$ = 305 µM, [NaCl] = 1.3 mM, [$NaNO_3$] = 98.6 mM, [NaBr]$_o$ = 4.5 µM (chlorination experiments) or 130 µM (bromination experiments), T = 20.00 ± 0.01 ºC. Quenchers included TMB or sodium thiosulfate with concentrations of 500 µM and 450 µM, respectively, at the time of quenching (i.e., after reaction aliquots were combined with the solution containing a quencher).

[b] % difference = $\left(\frac{k_{\text{obs,TMB}} - k_{\text{obs,thiosulfate}}}{k_{\text{obs,thiosulfate}}}\right) \times 100\%$

chlorination and bromination rate constants associated with TMB as a quencher were not significantly different (at the 95% confidence level) from those associated with sodium thiosulfate as a quencher. Furthermore, for dimethenamid chlorination experiments, average recoveries (± 95% confidence intervals) of free chlorine and TMB were 100.2% (± 0.7%) and 101.2% (± 0.6%), respectively. For dimethenamid bromination experiments, average recoveries of free chlorine, free bromine, and TMB were 100.4% (± 0.9%), 94.5% (± 1.5%), and 106.2% (± 0.8%), respectively. For all experiments involving chlorination or bromination of dimethenamid, monitored dihalogenated products of TMB (i.e., 2,4-dichloro-1,3,5-trimethoxybenzene, 2,4-dibromo-1,3,5-trimethoxybenzene, and 2-bromo-4-chloro-1,3,5-trimethoxybenzene) accounted for < 0.3% of total the total initial TMB concentration. Together with the data reported for chlorination of 2,4-DCP and bromination of anisole, these findings demonstrate the ability of TMB to facilitate quenching and, when Cl-TMB and Br-TMB are monitored, halogen-specific quantification of free chlorine and free bromine residuals in batch reactors simulating water disinfection conditions.

3.5 Competitive quenching of free chlorine. To assess the rate at which TMB reacts with free chlorine relative to four traditional quenchers, competitive quenching experiments were conducted at pH 7.10 in batch reactors that initially contained approximately equimolar concentrations (~52 µM each) of free chlorine, TMB, and one non-TMB quencher (Na_2SO_3, $Na_2S_2O_3$, ascorbic acid, or NH_4Cl). A reactor containing equimolar concentrations (~52 µM each) of free chlorine and TMB only served as the control. The concentrations of unreacted TMB and Cl-TMB in each reactor after quenching are reported in **Table 2**. In the control reactor, most of the initial TMB was converted into Cl-TMB via reaction with free chlorine ([Cl-TMB]/([Cl-TMB] + [TMB]) = 89%). When a non-TMB quencher was present, however, only a small percentage of the initial TMB was converted into Cl-TMB. Values of [Cl-TMB]/([Cl-TMB] + [TMB]) were ≤ 0.70% for Na_2SO_3, $Na_2S_2O_3$, and ascorbic acid, while that for NH_4Cl was 13%. We note that the value of [Cl-TMB]/([Cl-TMB] + [TMB]) in the control reactor was less than 100%, and the TMB mass balances (computed as [TMB] + [Cl-TMB]) in these experiments somewhat exceeded the nominal $[TMB]_o$ (52 μM). These discrepancies reflect the difficulty in ensuring that $[HOCl]_{tot,o} = [TMB]_o = [\text{non-TMB quencher}]_o$. The higher-than-expected TMB mass balances suggest that formation of the dichlorinated form of TMB did not occur to any appreciable extent, consistent with the anticipated lower nucleophilicity of Cl-TMB relative to TMB due to the ability of Cl to deactivate aromatic moieties toward electrophilic substitution.[18] (For experiments reported herein involving bromination, substituting an H atom with Br is also anticipated to attenuate the nucleophilicity of the halogenated product relative to the parent compound, as has been previously observed for bromination of anisole.[22]) The lower-than-expected value of [Cl-TMB]/([Cl-TMB] + [TMB]) in the control reactor and variations in TMB mass balances in different reactors should not, however, affect interpretation of the trends in [Cl-TMB]/([Cl-TMB] + [TMB]) values.

Table 2. Results from Competitive Quenching Experiments [a]

Non-TMB quencher	**Concentration (μM)**			$\frac{\textbf{[Cl-TMB]}}{\textbf{[Cl-TMB] + [TMB]}}$
	TMB	**Cl-TMB**	**Mass balance** [b]	
Sodium sulfite	59.38	0.36	59.74	0.61%
Sodium thiosulfate	52.49	0.23	52.71	0.43%
Ascorbic acid	55.32	0.37	55.69	0.67%
Ammonium chloride	49.52	7.15	56.67	13%
Control	6.03	48.11	54.14	89%

[a] Reaction conditions: pH 7.10, $[HOCl]_{tot,o} \approx [TMB]_o \approx [\text{non-TMB quencher}]_o \approx 52$ μM, [phosphate buffer] = 10 mM, ionic strength = 0.1 M

[b] TMB mass balance was calculated as the sum of [TMB] and [Cl-TMB]

The value of [Cl-TMB]/([Cl-TMB] + [TMB]) is indicative of the relative competitiveness of TMB for free chlorine. If TMB were to react with free chlorine more quickly than did a non-TMB quencher, the value of [Cl-TMB]/([Cl-TMB] + [TMB]) should approach 89% (the value of [Cl-TMB]/([Cl-TMB] + [TMB]) in the control reactor in which TMB was the only quencher present). In our experiments, the values of [Cl-TMB]/([Cl-TMB] + [TMB]) were close to zero when Na_2SO_3, $Na_2S_2O_3$, or ascorbic acid was present, indicating that these quenchers reacted with free chlorine much more rapidly than did TMB. The value of [Cl-TMB]/([Cl-TMB] + [TMB]) with NH_4Cl was higher (13%), but NH_4Cl still reacted with free chlorine more quickly than did TMB. These findings are consistent with the reactivity trend anticipated based on reported second-order rate constants for reactions of quenchers with free chlorine (**Table 3**): TMB < ammonia < ascorbate < sulfite < thiosulfate. For reactions with free bromine, TMB is predicted to be more competitive, noting that the reactivity of TMB toward free bromine (at pH 7) exceeds that of ammonia and ascorbate.

Table 3. Apparent Second-Order Rate Constants (k_{app}) for Reactions of Quenchers with Free Chlorine and Free Bromine [a]

	Free Chlorine			Free Bromine		
Quencher	k_{app} (M^{-1} s^{-1})	T (°C)	**Comments**	k_{app} (M^{-1} s^{-1})	T (°C)	**Comments**
TMB	563 ± 14	20	calculated from data in ref 16	$(3.28 \pm 0.14) \times 10^6$	20	current work [b]
ammonia	1.3×10^4	25	calculated in ref 19 from data in ref 31	4.1×10^5	20	calculated in ref 26 from data in ref 32
ascorbate	6×10^6	22	calculated from data in ref 33	$(1.7 \pm 0.2) \times 10^6$	22	pH 7.4; calculated in ref 26 from data in ref 34
sulfite	2.3×10^8	25	calculated in ref 19 from data in ref 35	1.9×10^9	25	calculated in ref 26 from data in ref 36
thiosulfate	1.8×10^9	25	calculated from data in ref 37	not reported	–	–

[a] Unless otherwise noted, all k_{app} values correspond to pH 7.0. Uncertainties represent 95% confidence intervals; uncertainties are not available for all k_{app} values calculated from the cited sources of data.

[b] k_{app} calculated as $k_{obs}/[HOBr]_{tot}$ from experiments performed at pH 7.1 (Figure S10A).

Despite the lesser reactivity of TMB toward free chlorine relative to traditional quenchers, results from the kinetic experiments reported above for chlorination of 2,4-DCP, bromination of anisole, chlorination of dimethenamid-P, and bromination of dimethenamid-P indicate that TMB can serve as an effective quencher of free chlorine and free bromine for reactions with half-times ≥ 0.5 min. Based on previously reported second-order rate constants for reactions of TMB with Cl_2, Cl_2O, and HOCl,[16] k_{obs} for TMB chlorination is calculated as 7.2×10^{-2} s^{-1} under the conditions employed for chlorination of 2,4-DCP. This predicted k_{obs} for TMB chlorination is close to an order of magnitude larger than the experimentally determined k_{obs} for 2,4-DCP chlorination ($(8.5 (\pm 0.4) \times 10^{-3}$ s^{-1}). These results suggest that TMB will serve as a satisfactory quencher (i.e., Q ≥ 100, **eqn 1**, where $k_{obs} = k_{app}[\text{free halogen}]$) when [TMB] exceeds [2,4-DCP] by a factor ≥12. Accordingly, satisfactory quenching of the 2,4-DCP chlorination experiments (**Fig. 1**, for which $[\mathrm{TMB}]_o/[\text{2,4-DCP}]_o = 120$) could have theoretically been achieved using less TMB (so long as $[\mathrm{TMB}]_o/[\mathrm{HOCl}]_{tot,o} > 1.0$). When quantitation of residual free chlorine is also desired, somewhat larger excesses of TMB (e.g., $[\mathrm{TMB}]_o/[\mathrm{HOCl}]_{tot,o} > 3$) will facilitate these measurements by minimizing the formation of dichlorinated TMB.

For the net bromination of anisole at pH 7.48, $k_{obs,anisole} = k_{obs,I} + k_{obs,II} = 8.33 \times 10^{-4}\ \mathrm{s}^{-1}$ (see **eqn 3** and **Table S9**) and therefore $k_{app,anisole} = k_{obs}/[\mathrm{HOBr}]_{tot} = 6.4\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$. Based on results that will be discussed in Section 3.6, $k_{\mathrm{app,TMB}} = 3.16\ (\pm\ 0.13) \times 10^{6}\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$ at pH 7.48. Entering these k_{app} values for anisole and TMB into **eqn 1** indicates that TMB will serve as a satisfactory quencher ($Q \geq 100$) when $[\mathrm{TMB}]/[\mathrm{anisole}] \geq 2.0 \times 10^{-4}$ (so long as $[\mathrm{TMB}]_o > [\mathrm{HOBr}]_{tot,o} + [\mathrm{HOCl}]_{tot,o}$).

For bromination of dimethenamid-P at pH 8.00 (**Table 1**), $k_{\mathrm{app,dimethenamid-P}} = 250\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$. At pH 8.00, $k_{\mathrm{app,TMB}} = 2.79\ (\pm\ 0.12) \times 10^{6}\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$ (see Section 3.6 below). These findings suggest that TMB will be sufficiently reactive as a quencher (i.e., $Q \geq 100$, **eqn 1**) when $[\mathrm{TMB}]_o/[\text{dimethenamid-P}]_o \geq 0.01$. In practice, $[\mathrm{TMB}]_o/[\mathrm{HOBr}]_{tot,o}$ must, however, exceed 1.0 to permit stoichiometric quenching of free bromine and to minimize formation of dibrominated and tribrominated TMB. For the experimental results shown in **Table 1**, $[\mathrm{TMB}]_o/[\text{dimethenamid-P}]_o \approx 50$, once again indicating that satisfactory quenching could have been achieved using less TMB.

3.6 Reactivity of TMB toward free bromine. Rate constants corresponding to reactions of TMB with free bromine ($k_{\mathrm{obs,TMB}}$, s^{-1}) were determined using competition kinetic experiments with dimethenamid-P serving as the reference compound. HOBr, with $\mathrm{p}K_a = 8.70$ (20 °C),[38] is anticipated to be the most abundant constituent of free bromine in solutions at near-neutral pH. In addition to HOBr, several other electrophilic bromine species (e.g., BrCl, $\mathrm{Br_2}$, BrOCl) can conceivably influence overall bromination rates of TMB, as has been observed for bromination of anisole,[22] dimethenamid-P,[21] and salicylic acid.[27] To explore the possible influence of the aforementioned bromine species on bromination kinetics of TMB, competition kinetics experiments were performed as a function of added NaCl, NaBr, and NaOCl (all at pH ≈ 7). The concentration of added NaCl (from 14 – 37 mM) did not appreciably influence $k_{\mathrm{obs,TMB}}$ (**Fig. S10A**). This finding suggests that BrCl, whose concentration is proportional to [Cl^-] (**eqn 5**), is not influencing overall bromination rates of TMB under the examined conditions.

$$\mathrm{HOBr(aq)} + \mathrm{Cl^-} + \mathrm{H^+} \rightleftharpoons \mathrm{BrCl(aq)} + \mathrm{H_2O}$$
$$\log K_3 = 4.09\ (20\ ^\circ\mathrm{C})^{39} \qquad (5)$$

As the concentration of NaBr (added in excess of NaOCl) increased from 15 – 31 μM, $k_{\mathrm{obs,TMB}}$ values did not increase (**Fig. S10B**). These results indicate that Br_2, whose concentration is proportional to the concentration of unoxidized Br^- (**eqn 6**), is unimportant as a brominating agent of TMB in our reactors under the experimental conditions described in Section 2.6.

$$\mathrm{HOBr(aq)} + \mathrm{Br^-} + \mathrm{H^+} \rightleftharpoons \mathrm{Br_2(aq)} + \mathrm{H_2O}$$
$$\log K_4 = 8.40\ (20\ ^\circ\mathrm{C})^{40} \qquad (6)$$

Changes in the concentration of NaOCl (from 20 – 34 μM, added in excess of NaBr) also did not appear to increase the values of $k_{\mathrm{obs,TMB}}$, thereby suggesting that BrOCl (whose concentration is proportional to [HOCl], **eqn 7**) does not substantially contribute to bromination rates of TMB.

$$\mathrm{HOBr(aq)} + \mathrm{HOCl(aq)} \rightleftharpoons \mathrm{BrOCl(aq)} + \mathrm{H_2O}$$
$$\log K_5 = -0.46\ (25\ ^\circ\mathrm{C})^{21} \qquad (7)$$

Br_2O is an additional free bromine species that can conceivably influence bromination rates of organic compounds. For reactions of anisole,[22] salicylic acid,[27] dimethenamid-P,[21] and *p*-xylene,[41] Br_2O was shown to be a minor (or imperceptible) contributor to overall bromination rates under most examined solution conditions. Compared to the previously examined organic compounds, TMB is more nucleophilic and should therefore react preferentially with more abundant, but less electrophilic, brominating agents such as HOBr (vis-à-vis the reactivity-selectivity principle[18]). Collectively, these findings suggest that Br_2O is unlikely to influence overall bromination rates of TMB in solutions of free bromine.

Second-order rate constants for reactions of dimethenamid-P with BrCl, Br_2, BrOCl, Br_2O, and HOBr have been reported[21] and permit calculations of how these brominating agents affect bromination rates of dimethenamid-P under a variety of solution conditions. Such calculations are important for the competition kinetics method employed herein (see ESI for additional details).

Given the putative unimportance of free bromine species such as BrCl, Br_2, BrOCl, and Br_2O in reactions with TMB in our systems, a second-order rate constant for the reaction of TMB with HOBr ($k_{\mathrm{HOBr,TMB}}$, $\mathrm{M^{-1}\ s^{-1}}$) can be approximated via:

$$k_{\mathrm{HOBr,TMB}} = \frac{k_{\mathrm{obs,TMB}}}{[\mathrm{HOBr}]} \qquad (8)$$

where the average $k_{\mathrm{obs,TMB}}$ value obtained from the variable [NaCl] experiments (**Fig. S10A**) was used to calculate $k_{\mathrm{HOBr,TMB}}$ as 3.35 (± 0.14) × 10^6 $\mathrm{M^{-1}\ s^{-1}}$. Relying on the variable [NaCl] experiments afforded the most precise estimate of $k_{\mathrm{HOBr,TMB}}$ of the data sets shown in **Fig. S10**.

3.7 Influence of quenchers on DBP stability. While high reactivity with free chlorine and free bromine is a defining trait of an effective quencher, inertness toward the analytes of interest is equally important. To assess the stabilities of eight DBPs in the presence of TMB, week-long experiments were conducted in batch reactors at pH 7.0 with $[\mathrm{TMB}]_o \geq 10 \times [\mathrm{DBP}]_o$. The stabilities of the DBPs were also evaluated in the presence of Na_2SO_3, $Na_2S_2O_3$, ascorbic acid, and NH_4Cl under similar conditions. These eight DBPs were selected for study because the influence of various quenchers on their stabilities has been examined in the literature,[2, 4, 5] thus allowing comparisons to the results of previous investigations. The results are summarized in **Table 4**, with check marks denoting negligible differences in DBP concentrations from those in the control reactors (which did not contain quenchers) after 7 days.

Table 4. Influence of Quenchers on the Stabilities of DBPs [a]

DBP	TMB	Ammonium chloride	Sodium thiosulfate	Ascorbic acid	Sodium sulfite
Chloropicrin	✓	✓			
Chloral hydrate	✓	✓	✓	✓	✓
Chloroacetonitrile (MCAN)	✓	✓	✓	✓	✓
Dichloroacetonitrile (DCAN)	✓	✓	✓	✓	✓
Trichloroacetonitrile (TCAN)	Inherently unstable in water, so quenchers make little difference				
Bromoacetonitrile (MBAN)	✓	✓		✓	✓
Dibromoacetonitrile (DBAN)	✓	✓	✓	✓	
Tribromoacetaldehyde (TBAL)	Inherently unstable in water, so quenchers make little difference				

[a] Check marks indicate that changes in DBP concentrations are not appreciably different from those in the control reactor without any quencher.

Chloropicrin was stable in the presence of TMB, in the presence of ammonium chloride, and when no quencher was present (**Fig. 4A**). On the other hand, the concentration of chloropicrin decreased substantially in the presence of Na_2SO_3, ascorbic acid, and $Na_2S_2O_3$. Na_2SO_3 and ascorbic acid led to no detectable chloropicrin after 1 day and 3 days, respectively. $Na_2S_2O_3$ led to a more gradual degradation of chloropicrin, with 42% of the initial chloropicrin concentration remaining after 7 days. Previous researchers found that dichloronitromethane was the major transformation product of chloropicrin in the presence of Na_2SO_3.[4] The degradation of chloropicrin in the presence of ascorbic acid has also been documented,[5] but to our knowledge the adverse impact of $Na_2S_2O_3$ on chloropicrin stability has not been previously reported.

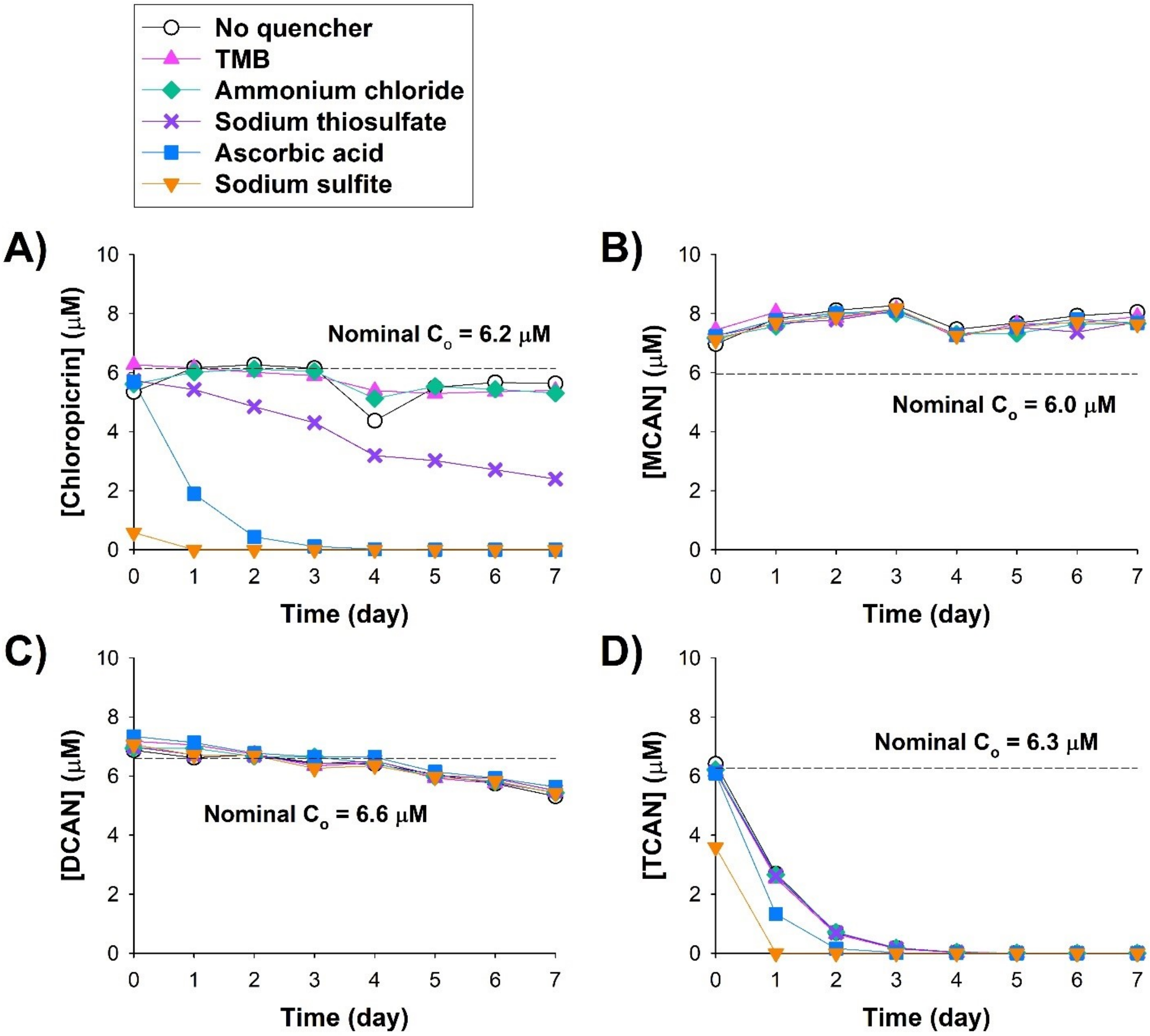


Fig. 4. The stability of **(A)** chloropicrin, **(B)** chloroacetonitrile (MCAN), **(C)** dichloroacetonitrile (DCAN), and **(D)** trichloroacetonitrile (TCAN) in the presence of various quenchers at pH 7.0. Reaction conditions: $[\mathrm{DBP}]_o = 6\ \mu\mathrm{M}$, $[\mathrm{quencher}]_o = 60\ \mu\mathrm{M}$, $[\mathrm{phosphate\ buffer}]_o = 10\ \mathrm{mM}$.

TMB did not have any discernible effect on the stabilities of chloroacetonitriles, although the effect of other quenchers depended on the identity of the DBP. Chloroacetonitrile (MCAN) was stable at pH 7.0 regardless of which quencher was present (**Fig. 4B**). Dichloroacetonitrile (DCAN) concentrations decreased by ~23% over 7 days in all reactors (**Fig. 4C**), ostensibly due to base-catalyzed hydrolysis to form dichloroacetamide.[42] The presence of quenchers did not have any appreciable effect on the rate of DCAN hydrolysis. Trichloroacetonitrile (TCAN) is inherently unstable at pH 7.0, as evidenced by its disappearance from the control reactor within 4 days (**Fig. 4D**). Previous researchers found that TCAN undergoes base-catalyzed hydrolysis to form trichloroacetamide and trichloroacetic acid.[43] We observed that Na_2SO_3 and ascorbic acid enhanced the rate of TCAN disappearance, causing TCAN to become undetectable after 1 day and 2 days, respectively. The disappearance of TCAN in the reactor containing Na_2SO_3 was accompanied by the generation of DCAN (data not shown), which agrees with previous research showing that TCAN is converted into DCAN in the presence of Na_2SO_3.[4] DCAN formation was not observed when ascorbic acid was present; accordingly, the product of reaction between TCAN and ascorbic acid merits further investigation.

TMB did not affect the stabilities of the bromoacetonitriles examined herein, but certain other quenchers did affect their stabilities. Bromoacetonitrile (MBAN) was stable in the absence of quenchers as well as in the presence of TMB, NH_4Cl, ascorbic acid, or Na_2SO_3 (**Fig. 5A**). $Na_2S_2O_3$, however, led to a 67% decrease in [MBAN] over 7 days. No degradation products of MBAN were detected using our analytical method. Dibromo-acetonitrile (DBAN) concentrations decreased by ~15% over 7 days in the absence of quenchers (**Fig. 5B**), most likely due to the hydrolysis of DBAN to form dibromoacetamide.[42] TMB,

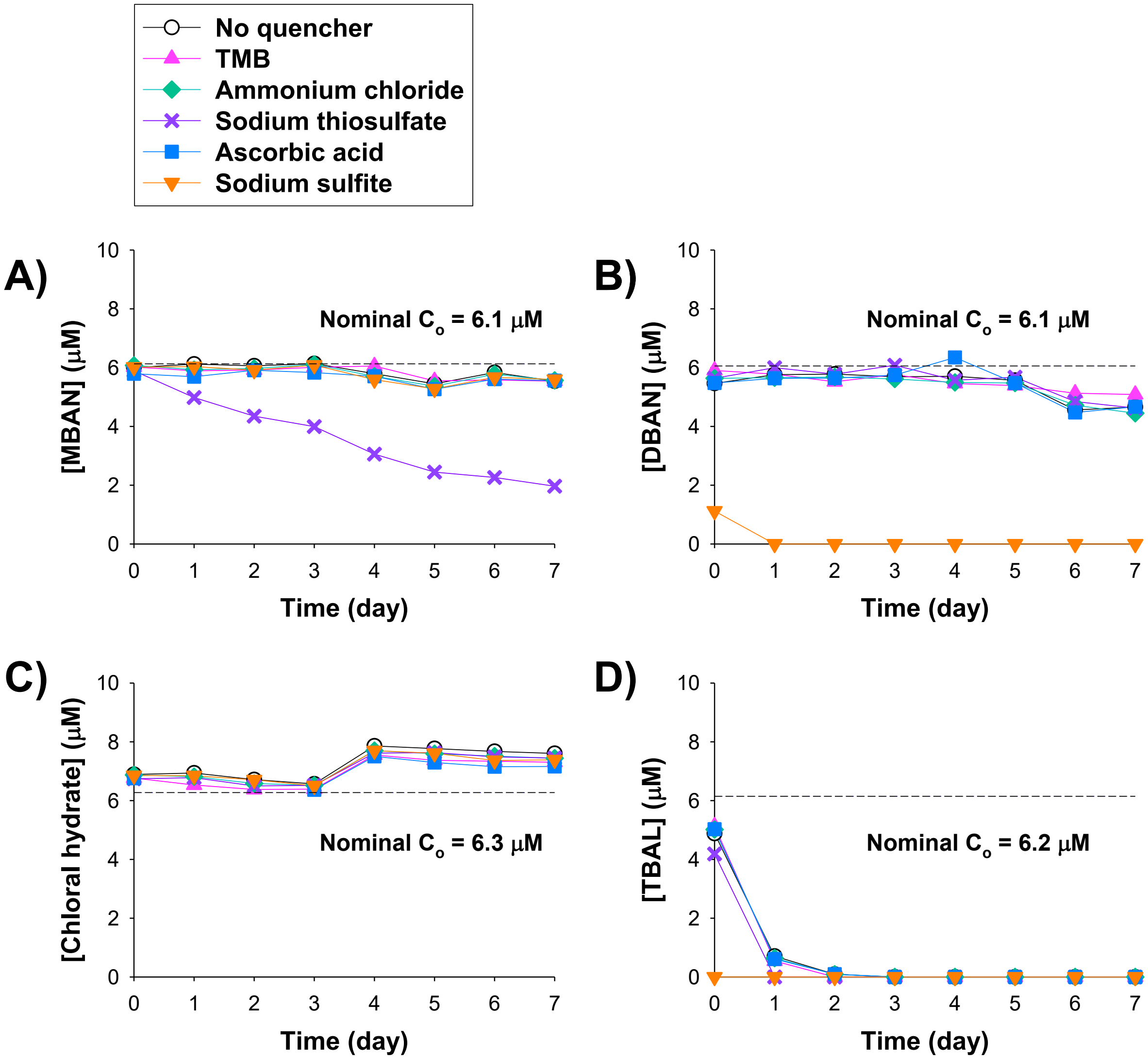


Fig. 5. The stability of **(A)** bromoacetonitrile (MBAN), **(B)** dibromoacetonitrile (DBAN), **(C)** chloral hydrate, and **(D)** tribromoacetaldehyde (TBAL) in the presence of various quenchers at pH 7.0. Reaction conditions: $[\mathrm{DBP}]_o = 6$ μM, $[\mathrm{quencher}]_o = 60$ μM, $[\mathrm{phosphate\ buffer}]_o = 10$ mM.

NH_4Cl, ascorbic acid, and $Na_2S_2O_3$ did not enhance DBAN hydrolysis. Na_2SO_3, on the other hand, caused DBAN to become undetectable within 1 day. The major degradation product was previously reported to be MBAN;[4] we observed the conversion of DBAN into MBAN in our experiment, and mass balances (computed as [MBAN] + [DBAN]) did not vary appreciably over 7 days (data not shown).

The stability of chloral hydrate was not affected by TMB or by any of the other quenchers tested (**Fig. 5C**). Our results are in contrast with previous work showing that when ascorbic acid was present, the concentration of chloral hydrate decreased by 11% in 1 day and then decreased further by 6% after 18 days.[2] Low recoveries of chloral hydrate in the presence of NH_4Cl have also been reported.[44] The discrepancy between our findings and those in previous studies may be explained by differences in experimental conditions, although further investigation is warranted.

Tribromoacetaldehyde (TBAL), like TCAN, was inherently unstable in aqueous solutions at pH 7.0 (**Fig. 5D**). TBAL became undetectable after 2 days in the absence of any quencher, and the presence of TMB, ammonium chloride, and ascorbic acid did not affect its degradation rate appreciably. In the presence of $Na_2S_2O_3$, TBAL disappeared more quickly than in the presence of non-sulfur-based quenchers. When Na_2SO_3 was present, the concentration of TBAL fell below the detection limit after only 10 min of reaction time. Previous researchers identified bromoform as the major product of TBAL hydrolysis, although the incomplete mass balance indicated that additional products were formed.[45]

As shown in **Table 4**, $Na_2S_2O_3$, ascorbic acid, and Na_2SO_3 would not be appropriate quenchers for chloropicrin. In addition, Na_2SO_3 should not be used when analyzing DBAN, while $Na_2S_2O_3$ should be avoided for MBAN. TCAN and TBAL are inherently unstable in water at pH 7.0, so the presence of quenchers has little influence on their stabilities. TMB and NH_4Cl did not adversely affect the stabilities of any of the DBPs tested since they do not serve as facile reducing agents for organic compounds. Thus, both TMB and NH_4Cl could serve as quenchers for free chlorine, with the caveat that NH_4Cl should only be used if the analytes of interest do not react with monochloramine (formed via free chlorine + excess NH_4Cl). When free bromine is present, using NH_4Cl to quench free halogens is not recommended due to the formation of bromamines, which are more reactive toward organic compounds than are chloramines.[12, 13]

3.8 Chloramination of TMB. To assess whether monochloramine could interfere with the effectiveness of TMB as a selective quencher of free chlorine, we added TMB to an aqueous solution containing free chlorine and a molar excess of ammonium chloride (NH_4Cl) at pH 7.03. Monochloramine formation from free chlorine + NH_4Cl should be rapid under our experimental conditions.[46] Our results show that [TMB] decreased by ~7% over 7 hours, accompanied by an approximately stoichiometric increase in [Cl-TMB] over the same period (**Fig. S11**). In a control reactor to which NH_4Cl—but not free chlorine—was added, no Cl-TMB was detected after 7 hours (data not shown). These results suggest that TMB is insufficiently nucleophilic to serve as a quencher of monochloramine. If water samples are quenched with TMB and then stored for more than ~7 hours before analysis, however, the presence of monochloramine could lead to overestimation of free chlorine concentrations due to the formation of Cl-TMB from chloramination of TMB. Bromamines are anticipated to react more rapidly with TMB relative to chloramines; the potential utility of TMB as quencher of bromamines merits further investigation.[12, 13]

4. Conclusions

A novel method was developed for using TMB to quench free chlorine and free bromine. TMB proved effective as a quencher for chlorination and bromination kinetic experiments for a diverse set of organic compounds. TMB did not affect the stabilities of eight examined DBPs.

TMB is quantitatively converted into Cl-TMB and Br-TMB when present in sufficient (≥ 2-fold molar) excess relative to free chlorine and free bromine, respectively. For the chlorination of 2,4-dichlorophenol (2,4-DCP), there was no significant difference in the experimental pseudo-first-order rate constants (k_{obs}) for reactions quenched with TMB versus those quenched with $Na_2S_2O_3$. For the bromination of anisole, experimental k_{obs} values with TMB as the quencher agreed with values predicted for reactions quenched with $Na_2S_2O_3$. Good agreement between k_{obs} values obtained with TMB versus thiosulfate as a quencher were also obtained for chlorination and bromination kinetic experiments involving dimethenamid-P. Therefore, although TMB does not react with free chlorine as quickly as do traditional quenchers, TMB is able to serve as an effective quencher for halogenation reactions with half-times ≥ 0.5 min.

TMB did not degrade DBPs that were otherwise unstable in the presence of traditional quenchers. Ammonium chloride similarly did not destabilize the examined DBPs, but its utility as a quencher is limited to analytes that would not react with monochloramine. Using TMB as a quencher offers the additional benefit of being able to quantify residual free chlorine and free bromine via measurements of [Cl-TMB] and [Br-TMB], respectively, in quenched samples. Because Cl-TMB and Br-TMB can contribute to the total organic halogen (TOX) content of quenched samples, TMB would not be a suitable free halogen quencher in samples subjected to subsequent TOX analysis. Although chloramination of TMB is much slower than are reactions of TMB with free chlorine, the presence of chloramines in water samples could interfere with the use of Cl-TMB as surrogate for residual free chlorine if the quenched samples were not analyzed within a few hours of quenching. The applicability of TMB as a quencher in reactions aimed at quantifying classes of DBPs not examined herein (e.g., iodinated DBPs[47]) merits future examination.

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