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TAML/H_2O_2 Oxidative Degradation of Metaldehyde: Pursuing Better Water Treatment for the Most Persistent Pollutants

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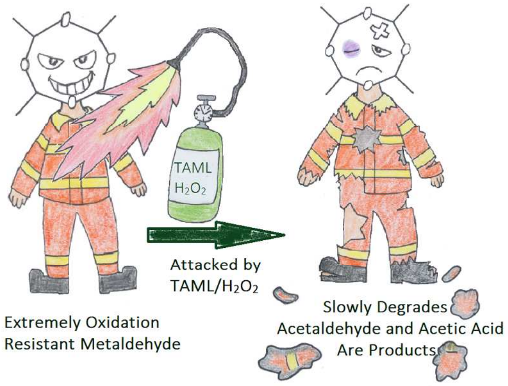

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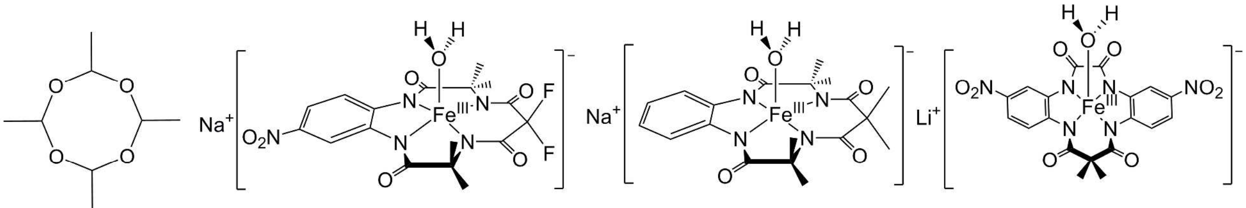
ABSTRACT. The extremely persistent molluscicide, metaldehyde, widely used on farms and gardens, is often detected in drinking water sources of various countries at concentrations of regulatory concern. Metaldehyde contamination restricts treatment options. Conventional technologies for remediating dilute organics in drinking water, activated carbon and ozone, are insufficiently effective against metaldehyde. Some treatment plants have resorted to effective, but more costly UV/H_2O_2. Here we have examined if TAML/H_2O_2 can decompose metaldehyde under laboratory conditions to guide development of a better real world option. TAML/H_2O_2 slowly degrades metaldehyde to acetaldehyde and acetic acid. Nuclear magnetic resonance spectroscopy (^{1}H NMR) was used to monitor the degradation—the technique requires a high metaldehyde concentration (60 ppm). Within the pH range of 6.5–9, the reaction rate is greatest at pH 7. Under optimum conditions, one aliquot of TAML **1a** (400 nM) catalyzed 5% degradation over 10 hours with a turnover number of 40. Five sequential TAML aliquots (2 μM overall) effected a 31% removal over 60 hours. TAML/H_2O_2 degraded metaldehyde steadily over many hours, highlighting an important long-service property. The observation of metaldehyde decomposition under mild conditions provides a further indication that TAML catalysis holds promise for advancing water treatment. These results have turned our attention to more aggressive TAML activators in development, which we expect will advance the observed technical performance.

Introduction

Metaldehyde, the cyclic tetramer of acetaldehyde (Chart 1), is deployed as a molluscicide to control gastropods including slugs and snails. It is one of the most recalcitrant anthropogenic water contaminants with a half-life in water of nearly 17 years.[1] Metaldehyde is toxic and even lethal to humans and other vertebrates at high doses.[2] At low concentrations in water, the broad distribution, moderate water solubility and enduring persistence conspire to make metaldehyde a contaminant of regulatory concern impacting, for example, UK, French and Swedish drinking water sources (Table S1).[3-6] The UK Environment Agency has reported that between 2009 and 2011 metaldehyde was found in 81 of 647 reservoirs in England and Wales.[7] In 2009, the UK Drinking Water Inspectorate (DWI) reported that metaldehyde was responsible for one third of the 1103 failures to meet the prescribed concentration or value (PCV) in these two countries.[8]



1a **1b** **2a**

Chart 1. Structure of metaldehyde and the TAML catalysts used in this study. TAML® is a registered trademark covering patented macrocyclic ligand catalysts.[9]

For most micropollutants, weighing the combined merits of familiarity and technical, cost and environmental performances has led to the conclusion that adsorption on activated carbon (AC), granular (GAC) or powdered (PAC), or oxidative degradation by ozone are the most desirable treatments. Metaldehyde is exceptionally difficult to remove using these technologies. GAC does not reliably achieve the regulatory PCV of 0.1 μg/L if the influent concentration is greater than 0.15 μg/L; peak concentrations in the rivers of Yorkshire can reach 0.4-0.6 μg/L.[8, 10-12] Similarly, reaching the PCV with PAC produces substantial AC waste.[13] Ozone by itself is ineffective at meeting the PCV.[8, 14] Thus, a substantial body of research has been dedicated to finding alternative methods. Table 1 lists the performance of selected processes with the relevant operational parameters.

Table 1. Summary of metaldehyde treatment protocols.

E#	Method	$[\mathrm{Met}]_0$ / mg L^{-1}	Efficiency[a]	Removal %	pH[b]	Experimental Details
1	UV_{254}/H_2O_2	0.002–0.02	0.07 $[H_2O_2]$	>95	natural	1500 mJ cm^{-2}, 272 mg L^{-1} H_2O_2[15]
2		1	3.50 $[H_2O_2]$	95	natural	600 mJ cm^{-2}, 272 mg L^{-1} H_2O_2[12]
3		1	3.38 $[H_2O_2]$	92	natural	1200 mJ cm^{-2}, 272 mg L^{-1} H_2O_2, 8.7 mgC L^{-1} DOC[12]
4		0.0005–0.003	0.14 $[H_2O_2]$	95	8	Pilot plant, 2600 mJ cm^{-2}, 20.4 mg L^{-1} H_2O_2[16]
5	UV_{254}/TiO_2	1	42 $[TiO_2]$	100	natural	600 mJ cm^{-2}, 24 mg L^{-1} TiO_2[12]
6		1	250 $[TiO_2]$	20	natural	1500 mJ cm^{-2}, 0.8 mg L^{-1} TiO_2[12]
7		1	2.92 $[TiO_2]$	7	natural	1200 mJ cm^{-2}, 24 mg L^{-1} TiO_2, 8.7 mgC L^{-1} DOC[12]
8		0.01	0.05 $[TiO_2]$	<50	natural	16800 mJ cm^{-2}, 100 mg L^{-1} TiO_2, 3.5 mgC L^{-1} DOC, 120 mg L^{-1} alkalinity[c, 17]
9	O_3	0.00005–0.0002	0.002 $[O_3]$	4	NA	Surface water, 4 mg L^{-1} O_3[12]
10	O_3/H_2O_2	0.000.5–0.003	0.14 $[H_2O_2]$ 0.27 $[O_3]$	72	8	Pilot plant, 16–22 mg L^{-1} H_2O_2, 8 mg L^{-1} O_3[16]
11	O_3/H_2O_2 followed by UV_{254}	0.0005–0.003	0.17 $[H_2O_2]$ 0.34 $[O_3]$	90	8	Pilot plant, 1200 mJ cm^{-2}, 16–22 mg L^{-1} H_2O_2, 8 mg L^{-1} O_3[16]
12	The Arvia Process	0.011	0.000164 [Nyex]	>99	7	67 g L^{-1} dry Nyex, 4 treatment cycles, converted to CO_2[18]
13	SAFMS[d]	200	190 [SAFMS]	>95	NA	1 g L^{-1} SAFMS, converted to acetaldehyde[19]
14	GAC[d]	64	13 [GAC]	15	6.2	750 mg L^{-1} [11]
15	PAC[d]	62.20	160 [AX-21]	42	7	162 mg L^{-1} AX-21[13]
16		2.475	39 [AX-21]	39	7	24.5 mg L^{-1} AX-21[13]
17	PC[d]	64	76 [PC]	>90	6.2	750 mg L^{-1} PC[11]
18	**1a**/H_2O_2	58.4	18,000 [TAML] 50 $[H_2O_2]$	31	7	1.004 mg L^{-1} **1a**, 376 mg L^{-1} H_2O_2, converted to 3:1 acetic acid:acetaldehyde[e]

[a]We define efficiency in this study as $mg_{Met}\ g_{material\ input}^{-1}$ with the identity of the material input considered given in the brackets while noting that O_3, H_2O_2, TiO_2, Nyex, SAFMS, GAC, PAC, PC, and TAML encompass energy inputs not accounted for herein; [b]Natural pH means the pH of

the water was not adjusted; [c]Annular photoreactor; [d]Abbreviations: SAFMS: Sulfonic Acid Functionalized Mesoporous Silica, GAC: Granular Activated Carbon, PAC: Powdered Activated Carbon, PC: Tailored Phenolic Carbon; [e]This work.

UV/H_2O_2 is the most effective metaldehyde AOP treatment and exploits the high reactivity and low selectivity of the hydroxyl radical (•OH);[20] > 95% removal can be achieved (Table 1, E1). However, low concentrations of metaldehyde and the presence of NOM (as surrogates, Table1, E2–3) demand increases in expensive UV dosages to reach high removals.[12, 15, 16, 21] UV/TiO_2 can completely degrade metaldehyde (Table 1, E5). The approach is very sensitive to dissolved organic carbon (DOC, Table 1, E5 and 7).[12] Other efforts have been made to decrease the energy demands of •OH production. In a pilot trial, O_3/H_2O_2 was found to reduce metaldehyde by 72% (Table 1, E10) with a 33% energy reduction compared to UV/H_2O_2 (Table 1, E4). Ozone/H_2O_2 with a follow-up of UV gave an energy optimized reduction of 90% (Table 1, E11).[16]

The Arvia process, a continuous adsorption-electrochemical regeneration cycle coupling adsorption to graphite intercalating Nyex™ with electrochemical oxidation, can achieve 99% conversion of metaldehyde (Table 1, E12)—regenerative energy demands are high.[18] In situ acid catalyzed decomposition with sulfonic acid functionalized mesoporous silica (SAFMS) is capable of 95% reduction (Table 1, E13) proceeding via acetaldehyde which is adsorbed by an amine bearing macroporous ion exchange resin.[19] Phenolic resin-derived activated carbons (PC) adsorb metaldehyde (Table 1, E17) better than either GAC (Table 1, E14) or PAC (Table 1, E15);[11] concerns have been raised about leeching of phenolic components into treated water.[18]

The challenges of metaldehyde contamination underscore the need for remediation technologies that can deliver better technical, cost, environmental, and health performances. TAML activators (Chart 1) are a family of small-molecule, full functional peroxidase enzyme mimics[22] that catalyze the oxidation of hazardous environmental pollutants including, *inter alia*, polychlorophenols, natural and synthetic estrogens, pesticides, dyes, explosives, and active pharmaceutical ingredients by H_2O_2.[23-33] These catalysts have been investigated for low dose adverse effects using in vitro cellular (10^{-11}–10^{-5} M) and in vivo zebrafish (80 nM–250 μM) development assays—all three catalysts used herein showed no toxicity.[34, 35] We have examined the degradation of metaldehyde (0.3 mM) by H_2O_2 (5–10 mM) catalyzed by **1a, 1b** and **2a** (0.4–2 μM) under ambient conditions by following the rates of metaldehyde consumption, the product production and the efficiencies in catalyst and peroxide. The work proves that TAML/H_2O_2 can slowly degrade metaldehyde in laboratory experiments. We conclude by reflecting on how TAML processes might be advanced to provide a real world solution.

Experimental

Materials. All reagents, components of buffer solutions, and solvents were of at least ACS reagent grade and used as received. Metaldehyde (Acros, 99%) was recrystallized in ethanol[36] and stored at 4 ºC. Metaldehyde stock solutions (0.3 mM) were prepared by sonicating appropriate quantities of metaldehyde in buffered D_2O (99.9%, Cambridge Isotope Laboratories, Inc.) at room temperature for 3 h. Phosphate (0.01 M, pH 6.5-7.5) and carbonate (0.01 M, pH 9.0) buffers were prepared in D_2O and monitored with an Accumet™ AB15 pH meter at room temperature. The stated pH values of these D_2O solutions are uncorrected pH meter readings. TAML® activator **2a** was synthesized by published methods.[37] Compounds **1a** and **1b** were obtained from GreenOx Catalysts, Inc. **1b** was purified by column chromatography on C18-silica gel with a water/methanol eluent (95/5, v/v) prior to use. Stock solutions of TAML activators (2×10^{-4} M) were prepared in D_2O (**1a** and **1b**) or H_2O (**2a**), and stored at 4 ºC. Hydrogen peroxide stock solutions were prepared by diluting 30% aqueous H_2O_2 with D_2O. The concentration of H_2O_2 stock solutions were monitored daily by measuring the UV-Vis absorbance at 230 nm ($\varepsilon = 72.4\ M^{-1}cm^{-1}$).[38]

Instrumental. UV-Vis measurements were performed on an Agilent 8453 UV-Vis spectrophotometer equipped with an 8-cell transporter and thermostatic temperature controller. Solution temperatures were maintained at 25 ºC in capped quartz cuvettes (1.0 cm). 1D ^1H spectra were recorded at 300 K on a Bruker Avance^{TM} III 500 NMR spectrometer operating at 500.13 MHz. The water signal was suppressed using the presaturation experiment (zgpr) from the Bruker pulse programs library. Chemical shifts are reported in parts per million relative to TMSP (internal standard for water solutions). Each sample was scanned 128 times over 16.5 minutes. The Bruker TopSpin^{TM} 3.0 software was used to process the NMR data. Absolute integrals for each proton peak were used for quantification. Each data point with error bars is the average of three measurements. No measurable broadening of signals due to the accumulation of catalyst was observed at the catalyst quantities employed.

Results and Discussion

The use of NMR spectroscopy as a monitoring tool. The oxidation of metaldehyde was monitored by ^1H NMR. Presaturation[39, 40] was used to suppress water proton signals. Since an internal standard would have been susceptible to TAML/H_2O_2 oxidation, none was added. The quantification of metaldehyde and products was enabled by maintaining consistency of the RF power delivered to the coil in the NMR probe (90^o pulse), always tuning/matching the coil before each measurement, using the same number of scans and the same receiver gain. As a result, the intensities of the observed signals are directly proportional to the absolute quantities of the specific protons responsible for each signal.[40, 41]

The traditional method of detecting metaldehyde in an aqueous matrix involves solid phase extraction, dissolution in an organic solvent, and quantification by GC-MS.[42, 43] This study employs *in situ* NMR as a monitoring method because it conveys certain advantages over the traditional method, especially because the process is slow, including (1) the reaction can be analyzed without quenching or pre-treatment, (2) extraction of analytes into organic solvents or matrices is not required thereby reducing sources of experimental error, (3) the concentrations of proton-bearing products and substrate can be analyzed at the same time without intensity calibration,[39] (4) small molecules can be detected without derivatization,[44] (5) one sample can be analyzed at multiple time points without destruction, and (6) lower volume reaction mixtures can be analyzed with ease.[45] These characteristics enable the real-time identification and quantification of multiple analytes in a small reaction volume without risk of altering their molecular structures in the analytical procedure. Thus, we show that ^{1}H NMR is a powerful analytical tool for monitoring the degradation of metaldehyde at higher concentrations (~300 μM).

General observations. The oxidation of metaldehyde was monitored by ^{1}H NMR (Figure 1). The identities of the major products, acetic acid and acetaldehyde, were confirmed by spiking with authentic standards. More acetic acid was produced than acetaldehyde. These degradation products possess rat LD_{50} values of 3310 and 661 mg kg^{-1} (oral), respectively, significantly greater than that of metaldehyde (Table S1).[46-49]

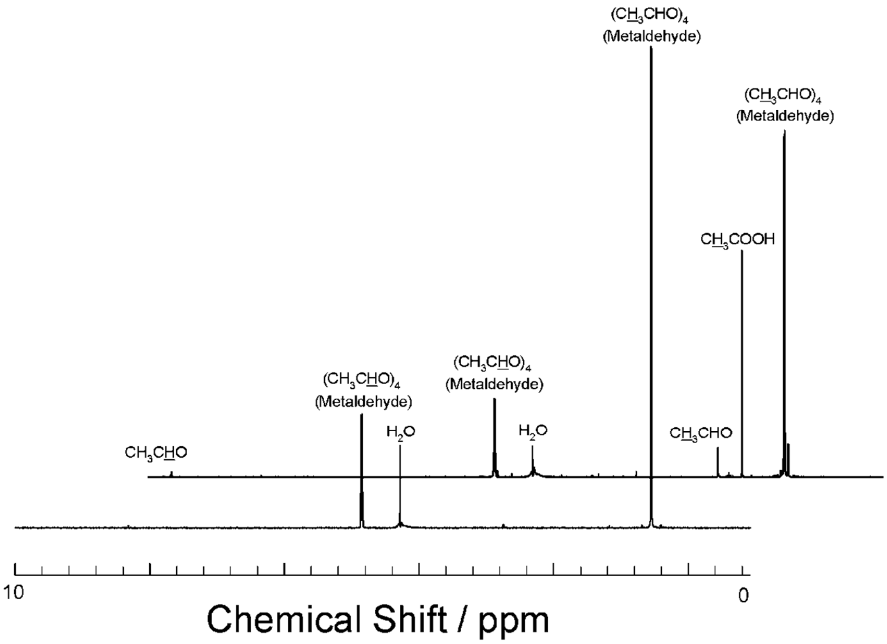


Figure 1. An example of the ^{1}H NMR spectra (in D_2O at pH 7) from which quantitative analyses were derived. Bottom spectrum collected at ca. 20 min, top at 60 h. Conditions: pH 7, 0.01 M phosphate buffer in D_2O, [Metaldehyde] = 3.18×10^{-4} M, [H_2O_2] = 5.30×10^{-3} M (180 ppm = 83% of the mineralization requirement), [**1a**] = 4.00×10^{-7} M. An additional aliquot of **1a** (total = 2 μM) was added to the reaction mixture every 12 h and an additional aliquot of H_2O_2 (total = 360 ppm) was added at 36 h.

Reactions were initiated by the addition of one aliquot of H_2O_2 to a solution of a TAML catalyst and metaldehyde in an NMR tube. The samples were stored in dark NMR autosampler holders throughout the measurement periods to minimize metaldehyde degradation by UV/H_2O_2.[12] Little decomposition of metaldehyde was observed in the presence of peroxide alone indicating that the uncatalyzed process does not contribute significantly to the observed degradation (Figures 2A and 1SA). As shown in Figures 2 and 1S, the rate of decomposition of metaldehyde as well as that of the production of acetic acid decreased over the reaction time period of 600 minutes. The production of acetaldehyde follows the same trend as that of acetic acid (Figure 2S).

Comparative performance of three catalysts in pH 7 buffered solutions. The relative performances of **1b** and **2a** in the degradation of metaldehyde were assessed for comparison with that of **1a** (Table 2). All **1** catalysts share the same basic ligand structure (Chart 1). Catalyst **1a** differs from **1b** by appendage of a nitro group to the aromatic ring and substitution of fluorine atoms for the geminal dimethyl groups of the malonamide residue.[50] These substitutions increase both the rate at which the catalyst is activated by H_2O_2 to form the active catalysts (Ac) and that at which Ac oxidizes a substrate at neutral pH.[50] The overall rate of TAML catalysis is typically a function of one or both of these processes. Addition of electron-withdrawing groups to the macrocycle typically increases the oxidative aggression of the resulting TAML catalyst. Consequently, the rate of metaldehyde oxidation catalyzed by **1a** was expected to be greater than that of **1b** as has been observed for other micropollutants.[29, 32] Indeed **1a** oxidized metaldehyde with a rate, r, of 8.36×10^{-2} min^{-1} where $r = d[S]/dt \times 1/[Fe]_0$, faster than **1b**, $r = 3.40 \times 10^{-2}$ min^{-1}. Activator **1a** also did more work than **1b** performing a 5% reduction with a turnover number (TON) of 40 versus a 1.8% reduction with a TON of 14 after 600 minutes. Catalysts **1** and **2a** belong to different generations.[51] In **1**, the amido-*N* nitrogen atoms are attached to six sp^2 and two sp^3 carbon atoms. In **2,** all eight carbons attached to the four amido-*N* nitrogen atoms are sp^2 hybridized, thereby significantly reducing the electron donating ability of the macrocycle. The introduction of a nitro group at each aromatic ring further reduces the overall basicity of the macrocycle of **2a** to further augment the reactivity. At neutral pH, **2a** is known to both form Ac from H_2O_2 and oxidize substrates more rapidly than any other TAML catalyst to date.[37] However, **2a** is less effective than either **1a** or **1b** in the degradation of metaldehyde showing a rate of 1.58 × 10^{-2} min^{-1}, an overall reduction of 1% and a TON of 8 under similar conditions. We attribute this to the shorter lifetime of **2a** versus **1a** or **1b**. Of the three catalysts tested, **1a** is the most effective in the degradation of metaldehyde considering both the amount and the rate of the decomposition.

Table 2. Summary of metaldehyde degradation under different conditions. $[H_2O_2] \approx 5 \times 10^{-3}$ M.

Cat	pH	[Cat] × 10^7 M	$[Met]_0 \times 10^4$ M	$r \times 10^2$ / min^{-1}[e]	TON	Met. Decomp. / %	CH_3COOH Formed / %[a]	t_∞ / min.
1a	7.0	4.00[b]	3.18	8.36	40	5	1.8	600
1b	7.0	4.33[b]	3.45	3.40	14	1.8	0.3	600
2a	7.0	3.90[b]	3.45	1.58	8	1.0	0.3	750
1a	7.0	4.00[c]	3.18	NA	NA	31.0	12	3640
1b	7.0	4.33[d]	3.45	NA	NA	3.5	1	1480
1a	NA	4.16[c]	3.33	NA	NA	7.0	4	3650
1a	6.5	4.16[b]	3.33	5.77	26	3.3	1	770
1a	7.5	4.16[b]	2.97	4.19	22	3.1	1	760
1a	9.0	4.16[b]	3.42	NA	NA	NA	0.4	770

[a]The percentage of acetic acid is calculated as a relative percentage compared to starting metaldehyde absolute integral ($Ac\% = (^{Abs}Int_{1.92})/(^{Abs}Int_{1.34})_0)$, i.e. if all metaldehyde is converted to acetic acid, the percentage will be 100%; [b]An aliquot of catalyst and an aliquot of H_2O_2 were added to the reaction mixture; [c]An aliquot of catalyst was added to the reaction mixture every 12 hours, five aliquots of catalyst were added in total and an additional aliquot of H_2O_2 was added to the reaction mixture at 36 h; [d]An additional aliquot of catalyst was added at 12 h; [e]The rate r is calculated from the slope of the line of best fit to the first three measurements of substrate concentration divided by catalyst concentration ($r = d[S]/dt \times 1/[Fe]_0$).

Effect of pH on the catalyzed oxidation process in buffered solutions. The trend in the rate of metaldehyde degradation with increasing pH differs substantially from that usually observed for TAML activators functioning in water. Here TAML catalysis follows a two-step stoichiometric mechanism.[26] The resting catalyst (Rc) is activated by H_2O_2 to form an active catalyst (Ac). Ac then oxidizes a substrate to give a product and regenerate Rc; both the first and second steps are comprised of multiple elementary reactions. The first step, catalyst activation, is typically rate-determining (d[S]/dt ~ $k_I[H_2O_2][Fe]$). In this system a linear dependence of the rate (*r*) of **1a** catalyzed metaldehyde oxidation on $[H_2O_2]$ (3–10 mM) was observed at pH 7 as would be expected for a system in which catalyst activation is rate determining (Figure 3S, Table S2). The value of the rate constant for TAML catalyst activation, k_I, follows a bell shaped trend with respect to increasing pH.[22, 50] For **1a**, k_I reaches a maximum value around pH 10.5.[50] As a result when catalyst activation is rate determining, the rate of substrate oxidation (d[S]/dt) is expected to increase as the proton concentration decreases if $[H_2O_2]$ and [Fe] are held constant within the pH range of 6.5-9.[50] At pH 6.5 in D_2O, the **1a** catalyzed metaldehyde oxidation *r* is 5.77×10^{-2} min^{-1}, lower than that observed at pH 7 (Table 2). However, the pH 7.5 *r* is 4.19×10^{-2} min^{-1}, also less than the pH7 *r* of 8.36×10^{-2} min^{-1} and no oxidation is observed at pH 9. Remarkably, the oxidation of metaldehyde at pH 6.5–7 follows the trend expected for a system in which catalyst activation is the rate-determining step. This seems to be unrealistic given the resilience of metaldehyde. Moreover, the behavior observed within the pH range of 7.5–9 is anomalous. We suspect this behavior has a complex origin which is being further examined. The maximum reaction rate within the pH range of 6.5–9 is achieved at ~ pH 7. A pH range of 7–10.5 is proposed for drinking water in order to achieve water quality objectives and corrosion control.[52]

*Multiple treatments with **1**/H_2O_2 in pH 7 buffered solutions.* The efficacy of multiple aliquots of **1a** in a solution buffered at pH 7 was determined (Figure 2, Table 2). The reaction was initiated by the addition of one aliquot of H_2O_2 to a buffered solution of **1a** and metaldehyde. An additional aliquot of the **1a** stock solution was added every 12 h. In total five aliquots of catalyst were added and the reaction was monitored for 60 h. One additional aliquot of H_2O_2 was added at 36 h. Metaldehyde consumption and acetic acid production ceased prior to each catalyst addition. Both resumed upon each addition of **1a**. We have long interpreted this result as evidence that the catalyst is undergoing inactivation during the slow oxidation process.[53, 54] The net effect of these treatments was a 31% reduction in the concentration of metaldehyde. Upon visual inspection of the data in Fig. 2, it appears that **1a** has a functional lifetime of 500 minutes. Adding successive catalyst aliquots at 500 minutes rather than 720 minutes, would give a total time of 42 hours rather than 60 hours, a 31% reduction of the stated time.

More complete metaldehyde degradation could have been achieved through further additions of catalyst. However, we chose to stop at this level of reduction to focus instead on the developments that might remove all of the metaldehyde with one TAML activator aliquot. This work is ongoing; we are optimistic that it will be successful.

Kinetic traces of the acetic acid production (Figure 4S) reveal a similar trend to that shown for acetaldehyde in Figure 2B. The acetic acid and acetaldehyde produced accumulate over multiple treatments and reach a final ratio of ca. 3:1, accounting for about half of the decomposed metaldehyde. The performance of **1b** under identical conditions was assessed for comparison. One aliquot of H_2O_2 was added to a buffered solution of **1b** and metaldehyde to initiate the reaction. An additional aliquot of the **1b** stock solution was added at 12 h. In total two aliquots of catalyst were added and the reaction was monitored for 24 h. These treatments effected a 3.5% reduction in the concentration of metaldehyde with a final ratio of acetic acid to acetaldehyde of 1.3:1 (Figure 5S); acetic acid is toxicologically preferred over acetaldehyde. For comparison the first two treatments with **1a**/H_2O_2 accomplished a 9% reduction in 24 h. In every way, of these two catalysts, **1a** has superior performance properties.

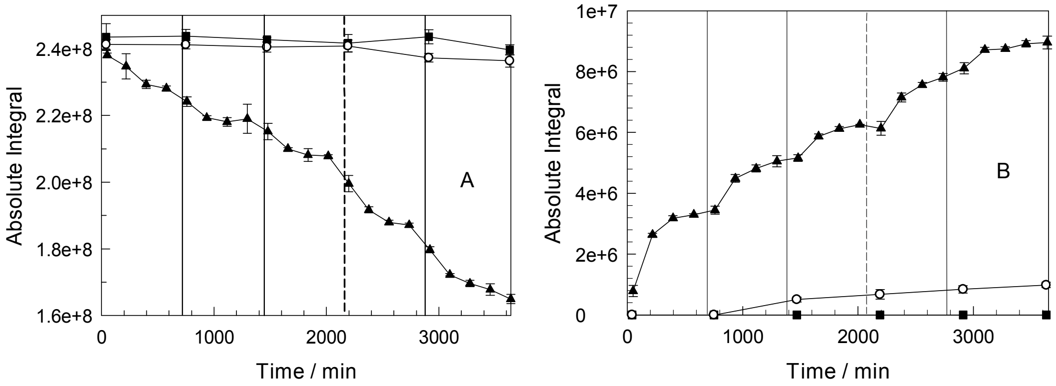


Figure 2. Metaldehyde reduction and acetaldehyde formation in pH 7 buffered D_2O. Symbols distinguish **1a** reaction from controls. Black squares: Metaldehyde; White circles: Metaldehyde and H_2O_2; Black triangles: Metaldehyde, H_2O_2, and **1a**. A: Reduction in the absolute integral of the signal corresponding to the metaldehyde CH_3 groups at 1.34 ppm with time (31% reduction at 3640 min). B: Increase in the absolute integral of the signal corresponding to acetaldehyde CH_3 groups at 2.25 ppm with time (3.7% production at 3640 min as a relative percentage of the initial absolute integral of the metaldehyde CH_3 groups). Conditions: pH 7, 0.01 M phosphate buffer in D_2O, [Metaldehyde] = 3.18×10^{-4} M, [H_2O_2] = 5.30×10^{-3} M, [**1a**] = 4.00×10^{-7} M. The vertical lines indicate the addition of an aliquot of **1a** every 12 h. The dashed vertical line indicates the addition of both an aliquot of **1a** and an aliquot of H_2O_2 at 36 h.

*Treatment with multiple aliquots of **1a**/H_2O_2 in an unbuffered solution.* The degradation of metaldehyde by multiple aliquots of **1a**/H_2O_2 in unbuffered D_2O was also followed as this approximates the ideal treatment conditions for large-scale water purification (Figure 3A). The reaction was initiated by the addition of one aliquot of H_2O_2 to an unbuffered solution of **1a** and metaldehyde. An additional aliquot of the **1a** stock solution was added every 12 h. In total five aliquots of catalyst were added and the reaction was monitored for 60 h. One additional aliquot of H_2O_2 was added at 36 hours. These treatments reduced the concentration of metaldehyde by 7%. The acetaldehyde produced by each aliquot of **1a** is rapidly consumed by the next aliquot of **1a** (Figure 3B), unlike catalysis in buffered solutions where it accumulates (Figure 2B). The final ratio of acetic acid to acetaldehyde was 6:1, an even more benign product mixture than that produced under buffered conditions. The consumption of acetaldehyde and comparatively acetic acid rich product ratio were interpreted as evidence of increased acetaldehyde oxidation over that which occurs in buffered solutions. Kinetic traces of acetic acid production (Figure 6S) show a trend similar to that observed in the buffered case (Figure 4S). The reduced metaldehyde decomposition is probably due, at least in part, to the lowering of the pH with the progression of the process in the absence of buffer. In a real world system where there would be much less metaldehyde this effect should be minimal. Again, these results indicate the need for a more aggressive, longer-lived TAML activator en route to being able to deal in the real world with this exceptionally persistent contaminant. As the reaction progressed through multiple additions of **1a**, the acetic acid $C\underline{H}_3$ signal drifted downfield (Figure 7S). This is indicative of a decreasing solution pH[45] consistent with the production and equilibrium protonation/deprotonation of acetic acid. The observed downfield shift in this unbuffered study was not observed in the buffered study. Since NMR study volumes (600 μL) were too small for accurate pH measurements, the signal drift was approximately reproduced in a model experiment whereby quantities of acetic acid were sequentially added to D_2O (Figure 8S).

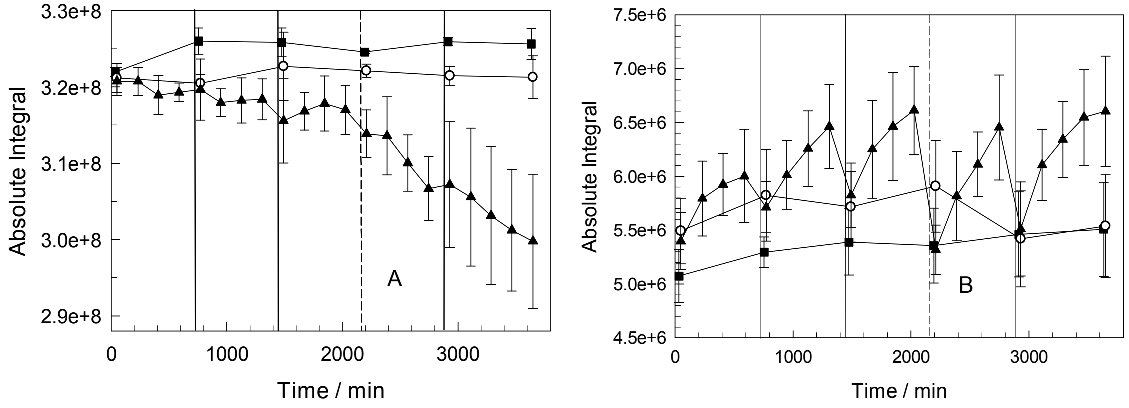


Figure 3. Metaldehyde reduction and acetaldehyde formation in unbuffered D_2O. Symbols distinguish **1a** reaction from controls. Black squares: Metaldehyde; White circles: Metaldehyde and H_2O_2; Black triangles: Metaldehyde, H_2O_2, and **1a**. A: Reduction in absolute integral of the metaldehyde CH_3 groups at 1.34 ppm with time (7% reduction at 3650 min). B: Acetaldehyde formed according to absolute integral at 2.25 ppm in the ^1H NMR spectra. Conditions: D_2O, [Metaldehyde] = 3.33×10^{-4} M, [H_2O_2] = 5.53×10^{-3} M, [**1a**] = 4.16×10^{-7} M. The vertical lines indicate the addition of an aliquot of catalyst to the reaction mixture every 12 h. The dashed vertical line indicates the addition of both an aliquot of catalyst and an aliquot of H_2O_2 at 36 h.

Comparison of TAML/H_2O_2 system with existing metaldehyde degradation processes. We have long known that TAML/H_2O_2 processes are very efficient in remediating water contaminants. The data in Table 1 quantify this for metaldehyde. The TAML process displays a peroxide efficiency of 50 mg_{Met} g_{H2O2}^{-1}, 14 times greater than the 3.50 mg_{Met} g_{H2O2}^{-1} of UV_{254}/H_2O_2 and 350 times greater than the 0.14 mg_{Met} g_{H2O2}^{-1} of O_3/H_2O_2. After the TAML process reported herein, UV_{254}/TiO_2 is the next most efficient reported catalytic metaldehyde oxidation process. Metaldehyde is oxidized by **1a**/H_2O_2 with an efficiency of 18,000 mg_{Met} g_{TAML}^{-1}, 72 times greater than 250 mg_{Met} g_{TiO2}^{-1}, the best reported efficiency of UV_{254}/TiO_2 (noting of course that only the surface of TiO_2 nanoparticles are active). The multiple aliquot process based on **1a**/H_2O_2 shows greater material efficiencies than GAC, PAC, or PC and remediates metaldehyde in situ.

While catalyst inactivation complicates comparisons of efficiency between **1a**/H_2O_2, the Arvia process and SAFMS, other qualitative comparisons can be made. Since TAML/H_2O_2 does not rely upon adsorption it is more likely to accommodate a range of substrates of varying structure than is the Arvia process. Since TAML/H_2O_2 is an oxidative process, it is likely to be more general than the acid catalyzed decomposition employed by SAFMS. SAFMS produces acetaldehyde exclusively which is also an ozone disinfection by-product. Acetaldehyde is considered a probable human carcinogen (Group B2)[55, 56] although no international guideline for acetaldehyde in drinking-water has been established. Chlorination of acetaldehyde containing water can result in the formation of chloral hydrate (trichloroacetaldehyde) which may subsequently degrade to chloroform depending on pH, temperature, and maturity of the water.[57] In all cases TAML processes produced more acetic acid than acetaldehyde.

Despite the comparative advantages, it is important to note that the metaldehyde degradation rates that we have characterized are slow for this especially persistent pollutant. We evaluate this work at its current state of development as very promising progress, but do not consider the system is ready yet as a real world solution in the particular case of this especially persistent micropollutant. Thus, it is worth asking how much faster a catalyzed process would have to proceed to represent a real-world solution for metaldehyde remediation. A ten-fold increase in the rate would result in the removal of one third of the metaldehyde in ca. 4 hours, all other things being equal. A one-hundred-fold increase in the rate would reduce this time to 24 min; a one-thousand-fold increase to 2.4 min. Is it conceivable that the higher rate increases might be achievable? In seeking shorter reaction times, we are redesigning the catalyst to increase *both* the lifetime and the aggression. The fact that this TAML/ H_2O_2 process is not ready for commercial development for metaldehyde remediation does not have the same meaning for the vast number of micropollutants that are much less oxidatively resistant than metaldehyde. An additional area for study involves the assessment of the interaction of NOM surrogates with TAML/H_2O_2.

It is also worth asking about the safety of any TAML process for water treatment. Multiple studies have been published on toxicity endpoints of TAML activators[32, 34, 35] and these studies are ongoing and include mammalian studies. Due to the diverse reactivity of the activated catalyst, catalysis relevant TAML inactivation can only be studied at $[\text{TAML}] < 1\times10^{-6}$ M under turnover conditions where the remaining concentration of substrate is greater than zero when all of the catalyst has been inactivated. The final result is a soup of degradation and catalyst inactivation products. The former are present in much larger amounts than the latter making the chemical identification of catalyst derived degradation products complicated. One study showed how a catalyst similar to **1b** was breaking down under oxidative stress.[58] Because of the challenges of chemical characterization, we have chosen to test final process solutions for toxicity.[32] Additional such studies are forthcoming.

Supporting Information. Supporting Information Available. Tables of metaldehyde properties and experimental results with varied conditions (Tables S1 and 2), figures of metaldehyde degradation details (Figures 1-8S). This information is available free of charge via the Internet at http://pubs.acs.org.

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