

Transformative Catalysis Purifies Municipal Wastewater of Micropollutants

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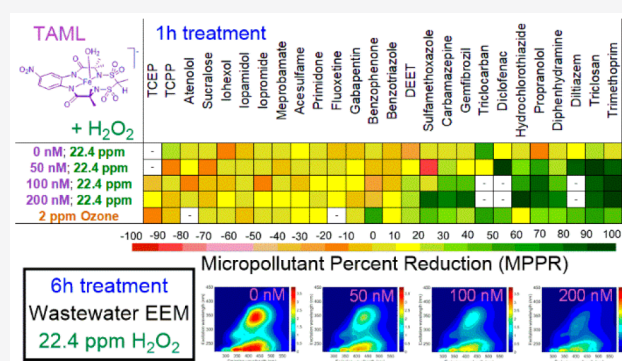
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ABSTRACT: We describe the use of TAML/peroxide to reduce micropollutants (MPs) in Tucson, AZ, secondary municipal wastewater. The laboratory studies establish simple-to-apply MP abatements rivaling ozone in technical performance. The approach rests on the latest-generation TAML catalyst, **2**, currently the highest-technical performance H₂O₂ activator across both chemistry and biology. Thirty-eight MPs were examined with five **2**/H₂O₂ treatments (50 nM **2** with 22.4 ppm H₂O₂, 100 nM **2** with 11.2 ppm H₂O₂, 100 nM **2** with 22.4 ppm H₂O₂, 200 nM **2** with 11.2 ppm H₂O₂, and 200 nM **2** with 22.4 ppm H₂O₂) and four ozone treatments (2, 4, 6, and 8 ppm). Satisfactory analytical data were returned for 25 MPs that were monitored kinetically (LC-MS/MS) from 6 min to 6 h. For all **2**/H₂O₂ conditions, decreases in MP concentration had either ceased at 30 min or showed marginal improvements at 1 h remaining constant to 6 h. The highest-performance **2**/H₂O₂ system (200 nM **2** with 22.4 ppm H₂O₂) outperformed 2 ppm ozone virtually across the board, delivering micropollutant percent reductions (MPPRs) of 26–98% corresponding to performance advantage ratios over 2 ppm ozone of ~0.9–8. These data indicate that **2** (1 kg at 70 nM) and H₂O₂ (53.55 kg at 11.2 ppm) would treat the daily wastewater output of 150,000 Europeans [150 L day⁻¹ (population equivalent)⁻¹, 22,500 tons total] in a manner comparable to that of a common ozone administration of 3 ppm, establishing a new approach worthy of further optimization for municipal wastewater MP treatment.

KEYWORDS: sustainable ultradilute oxidation catalysis (Sudoc), municipal wastewater treatment, micropollutants, catalysis, kinetics, TAML, ozone treatment



1. INTRODUCTION

The pollution of water by micropollutants (MPs) that exhibit adverse effects on aquatic life at low concentrations (≤ 2 ppb)^{1–3} is a global sustainability problem.⁴ The past 150 years have seen a massive expansion in both synthetic chemicals⁵ and chemically based economic activity that has resulted in worldwide contamination of water bodies by MPs of both synthetic and natural origins.^{4,6–11} Conventional wastewater treatment methods are insufficiently effective in removing MPs to protect aquatic life.^{7,12} For example, chlorination, typically utilized in disinfection, chemically changes some MPs; however, it also produces persistent and toxic chlorinated disinfection byproducts.^{13,14} To address the menace of MPs, Switzerland mandated in 2014 a 50% reduction in their releases and has begun adding additional ozone or activated carbon final treatment stages in ~100 of their ~650 wastewater treatment plants.^{15–17} The European Union is primarily focusing on optimizing ozone processes for treating MPs.¹⁸ However, while both ozone and ACs are viable solutions for larger plants in richer nations, neither appears to transfer easily to less wealthy and/or smaller jurisdictions. Thus, there

remains a pressing need for broadly usable, safe MP water treatment solutions.

TAML catalysts^{19–21} (Figure 1) are bioinspired, miniaturized replicas (typically <1% by mass) of the peroxidase enzymes that faithfully mimic the efficient enzymatic catalytic cycle.²² The latest-generation TAMLs (e.g., **2** is the current best overall technical performer) outperform their predecessors (e.g., **1**),¹⁹ which have been previously shown to activate peroxide to effectively degrade MPs, including pharmaceuticals,²³ pesticides,²⁴ natural and synthetic estrogens²⁵ and testosterone,²⁶ antimicrobials,²⁷ bacterial spores,²⁸ explosives,^{29,30} dyes,^{31,32} industrial chemicals including bisphenol A,³³ and many more.^{34,35} In a study on wastewater samples from a London Municipal Wastewater Treatment Plant

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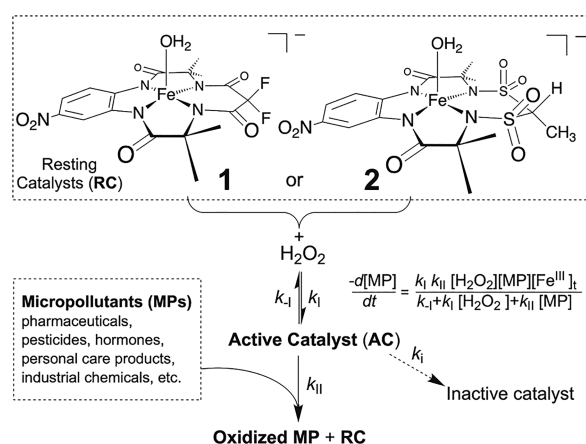


Figure 1. Structures of TAML 1, the best overall technical performer among prior generations, and TAML 2, the latest generation's current best technical performer, discussed or used in this paper and the general mechanism for 1- or 2-catalyzed oxidation of micropollutants (MPs). The k_{ii} (rate constant for substrate oxidation)/ k_i (rate constant for catalyst inactivation) ratio provides a quantitative measure of comparative catalyst performances.¹⁹ TAML activators are catalyst compositions of matter encompassed by U.S. Patents 6,100,394 and 10,926,248.

(MWWTP), the highest-performance earlier-generation TAML system, **1** (40 and 80 nM) with H₂O₂ (20 ppm), impressively degraded 11 priority MPs of the U.K. water industry present initially in parts per trillion to low parts per billion concentrations.³⁶ However, **1** is an organofluorine catalyst.

Following our long-standing precautionary logic,³⁷ while **1** is free of low-concentration toxicity in zebrafish development,³⁸ we strategically passed it over for real-world consideration because of the biochemically uncommon fluorine macrocyclic substituents and were rewarded through iterative design with even higher-performance TAML catalysts that are composed exclusively of biochemically common elements.¹⁹ Currently, **2** is the best technical performer among this latest generation of TAMLs; it is 10-fold more effective than **1** on the MP propranolol.¹⁹ Here we present the results of a detailed comparison of 2/H₂O₂ to ozone for treating MPs in the municipal wastewater of Tucson, AZ.

2. EXPERIMENTAL SECTION

2.1. Materials, Chemicals, and Reagents. TAML **2** was prepared as described elsewhere.^{19,20} H₂O₂ (50 wt % solution in water, stabilized) was purchased from ACROS Organics and standardized using Fe(SCN)₃.³⁹ Colorimetric measurements were performed using a H₂O₂ Single-Analyte Photometer (SAM) Kit (I-2016) consisting of Vacu-vials and a SAM photometer. Catalase (bovine liver, aqueous suspension, 45 mg/mL, 10,000–40,000 units/mg of protein) was purchased from Sigma-Aldrich and used without further purification. Analytical standards from Sigma-Aldrich (St. Louis, MO), Alfa Aesar (Ward Hill, MA), and US Pharmacopeia (Washington, DC) of >97% purity were employed. Isotopically labeled surrogate standards were purchased from Cambridge Isotope Laboratories (Andover, MA), Toronto Research Chemicals (Toronto, ON), C/D/N Isotopes (Pointe-Claire, QC), and Santa Cruz Biotechnology (Dallas, TX). Nanopure water was produced in house using a Barnstead Pure system. HPLC grade acetonitrile and methanol and ACS grade acetic acid

were purchased from Fisher Scientific (Fair Lawn, NJ). Whatman glass microfiber filters (grade GF/F, 47 mm and 0.7 μm pore size) were purchased from Fisher Scientific.

2.2. Sample Collection and Preparation. Secondary effluent from The Agua Nueva Water Reclamation Facility (WRF) in Tucson, AZ was filtered using Whatman glass microfiber filters and stored at 4 °C. All experiments were performed within 2 weeks of water collection. After the experiments, samples were filtered and 100 μL of 2 μg/L isotopically labeled surrogates was added to 900 μL of samples in a 2 mL vial prior to analyses. UVA 254 nm, TF, and EEM analysis were performed with 20 mL samples.

2.3. Indicator Micropollutants for Analyses. A list of indicator MPs (Table S1) comprising pharmaceuticals, personal care products, industrial or commercial chemicals, household chemicals, steroids or hormones (synthetic and natural), and pesticides were chosen on the basis of a priority scoring system (PSS)⁴⁰ involving (i) frequency of detection in wastewaters, (ii) mean concentration in wastewaters, and (iii) published literature for compounds detected in wastewater.

2.4. Instrumentation. MPs were analyzed using an Agilent 1290 ultra-high-performance liquid chromatography (UHPLC) instrument coupled with an Agilent 6490 tandem mass spectrometer (MS/MS). Separations of compounds were achieved on a nonpolar Agilent Zorbax eclipse Plus C8 column [2.1 mm × 100 mm, 1.8 μm (particle size), rapid resolution HD column] using a combination of water with (A) 0.1% acetic acid and (B) acetonitrile with 0.1% acetic acid as the mobile phases. This LC-MS/MS method is a modification of a previous method.⁴⁰ The LC method engaged a gradient elution of A and B, beginning with 5% B for the first minute and gradually increasing to 100% after 10 min. This was maintained for 4 min until shifting back to the starting conditions of 5% B. A flow rate of 0.35 mL/min and a sample injection volume of 80 μL were used for all samples. The mass spectrometer was run in dynamic multiple-reaction monitoring (MRM) mode, with analytes being ionized using electrospray ionization (ESI in both positive and negative modes), selected with triple quadrupoles (QQQ), and quantified using a high-energy dynode. The instrumental parameters for ESI-MS analyses and QQQ operations are detailed in Tables S2 and S3, respectively.

The instrument detection limits (IDLs) were determined by the lowest standard in the calibration curve with a signal-to-noise ratio of at least 3 (S/N > 3) and with at least 80% accuracy. Calibration points were at 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, 10, 20, 50, 100, 200, 500, and 1000 μg/L. Depending on where the analyte concentration within the sample fell, irrelevant calibration points on either end of the curve were decreased to increase linearity. All concentrations that were above the highest point in the calibration curve were diluted and reanalyzed. All analytes were calibrated externally using linear or power regression with 1/*x* weighting. Correlation coefficients were required to be at least 0.990 and typically exceeded 0.995. Isotope dilution was used for quantification of all analytes.⁴¹ The data were then processed with MassHunter Quantitative Analysis B.04.00. At least one lab blank, lab-fortified blank, and QC sample were studied out for every 10 samples.

2.5. Ozone Treatment. All ozone treatments and preparation and standardization of ozone stock solutions were performed as described in the literature.⁴²

2.6. 2/H₂O₂ Treatment. Stock solutions of **2** (1 × 10⁻⁵ M), H₂O₂ (1 M), and catalase (10,000 ppm) were prepared in

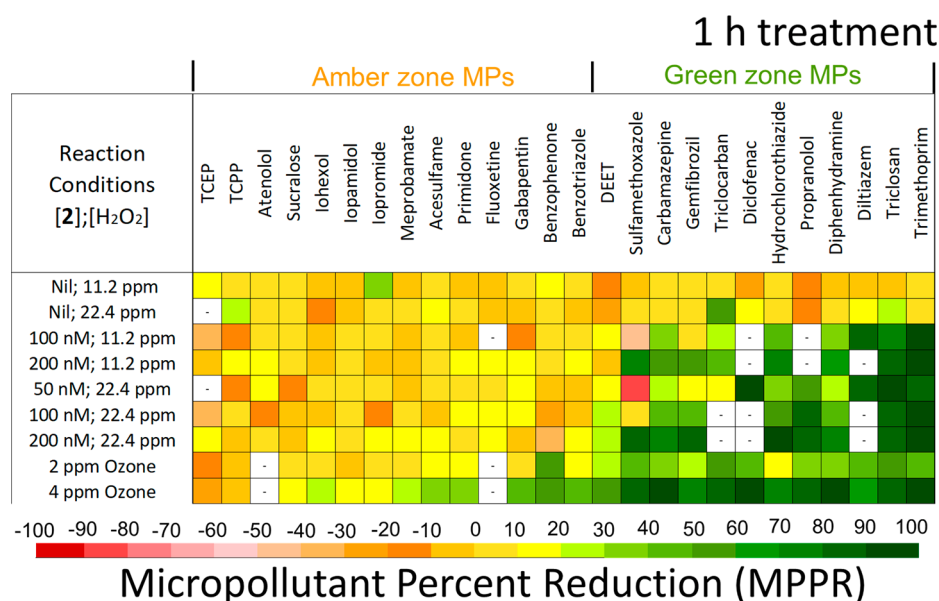


Figure 2. MP percent reductions (MPPRs) at 1 h for treatment of Tucson Agua Nueva MWWTP secondary wastewater: (i) control H₂O₂ (rows 1 and 2), (ii) 2/H₂O₂ (rows 3–7), and (iii) ozone (after 24 h, rows 8 and 9). All values are the average MPPRs from three separate experiments. White boxes indicate an MP could not be adequately quantified under the prescribed conditions. Reaction conditions: ambient wastewater pH, 25 °C, and ambient pressure. Abbreviations: TCEP, tris(2-chloroethyl) phosphate; TCPP, tris(1-chloro-2-propyl) phosphate; DEET, *N,N*-diethyl-3-methylbenzamide. Negative removals of MPs may be a result of the uncoupling of MP conjugates by 2 and H₂O₂ or may signal experimental limitations.

HPLC grade water. The secondary effluent sample was equilibrated to 25 °C in a water bath, and the reaction was initiated by adding appropriate aliquots of 2 and H₂O₂. At predetermined time intervals, aliquots were withdrawn, quenched with catalase, and analyzed for MPs by LC-MS/MS.

3. RESULTS AND DISCUSSION

3.1. Comparative Performance of 2/H₂O₂ and Ozone Treatments and Performance Advantage Ratios (PARs).

Samples of secondary wastewater from Tucson's Agua Nueva Wastewater Treatment Plant were treated with 2 and H₂O₂. MPs were selected by priority scoring⁴⁰ (38 examined, of which 26 were quantifiable). The 2/H₂O₂ micropollutant percent reductions (MPPRs) were obtained at various time points (6, 12, 20, 30, 40, 60, 120, 240, and 360 min) using five treatment conditions (three separate experiments for each condition set and time) with two H₂O₂ control conditions (1 h heat map in Figure 2; for other times, see Figure S1). The 2/H₂O₂ MPPRs were then analyzed to determine the conditions that best balance technical and likely cost performances and are compared with those of ozone (2 and 4 ppm) on the same water in Figure 2 and with higher ozone concentrations (6 and 8 ppm) (Figure S1). All ozone MPPRs were measured after exposure for 24 h rather than sooner to achieve a high likelihood that all ozone MP degradation processes were complete.

In Figure 2, MPs are arranged from left to right according to increasing MPPRs by both 2/H₂O₂ and ozone at 2 and 4 ppm. The right green heat map zone from *N,N*-diethyl-3-methylbenzamide (DEET) to trimethoprim spans MPs with typically good to excellent MPPRs. In the left amber heat map zone from tris(2-chloroethyl) phosphate (TCEP) to benzotriazole, minor (<20%) MPPRs were typically achieved for MPs for various 2/H₂O₂ conditions or for 2 ppm ozone. Small to moderate MPPRs were realized for some amber zone MPs

for less desirable ozone higher administrations beginning at 4 ppm and being maximized at 8 ppm. While adding additional aliquots of the catalyst typically increases the MPPRs of very persistent MPs,^{43,44} multiple 2 aliquots were avoided because they were outside the scope of this study; the idea was to discover where the results of various thought to be realistic sets of 2/H₂O₂ conditions fell on the 2–8 ppm O₃ performance span. Under the conditions studied, ozone has broader activity than 2/H₂O₂ only at higher ozone concentrations (3.5–8 ppm). Ozone becomes much less practical when the O₃ concentration exceeds 3.5 ppm. We did not increase the concentration of 2 to attempt to match the higher-O₃ concentration performances. Our preference in seeking improvements is to keep the TAML concentration as low as possible and increase the catalyst performance through catalyst design which is ongoing and certain to improve the demonstrated technical performances of 2.

Table 1 compares the green zone MPPRs for 2 and H₂O₂ to those of ozone treatments (2 ppm, a concentration deployed at the very high quality Neugut MWWTP in Dübendorf, Switzerland¹⁶) and lists the performance advantage ratios (PARs, in bold) of 2 and H₂O₂ across the many treatment conditions versus ozone (2 ppm). The PARs are the ratios of the varying 2/H₂O₂ MPPRs to the 2 ppm ozone MPPR; a PAR of >1 indicates 2/H₂O₂ outperforms 2 ppm ozone, and a PAR of <1 indicates 2 ppm ozone outperforms 2/H₂O₂. Ozone (2 ppm) produced final MPPRs of ~11–55%. After only 6 min, the 2 (200 nM)/H₂O₂ (22.4 ppm) process delivered superior MPPRs, compared to that of ozone (2 ppm), for all MPs (except sulfamethoxazole) of ~20–84%, increasing with time to superior performance for all MPs by 30 min and reaching 25–98% at 60 min (Figure 2), except for that of indeterminate triclocarban, which was moderately degraded by 46.4% by the 2 (200 nM)/H₂O₂ (11.2 ppm) process. The 60 min data remained unchanged overall through

Table 1. Green Zone MPPRs (entries are averages of three measurements) and PARs (bold)^a

treatment time (min)	DEET	sulfamethoxazole	carbamazepine	gemfibrozil	triclocarban ^d	diclofenac ^e	hydrochlorothiazide	propranolol	diphenhydramine	diltiazem ^e	triclosan	trimethoprim
6 ^c	21.6	-26	25.8	25.8	14.7	92.2	31.6	83.8	19.5	90	77.1	74.3
12 ^c	0.8	-0.5	0.7	0.9	0.3	2.2	2.8	2.7	0.5	2.1	1.4	1.7
	22.8	43.2	34.9	45.1	34.3	92.2	54.2	86.2	37.2	90	75.6	95.7
20 ^c	0.8	0.9	0.9	1.5	0.7	2.2	4.8	2.8	1.0	2.1	1.4	2.2
	31.7	72.1	51	55.7	45.2	92.2	67.2	86.6	54.2	90	84.2	98
30 ^c	1.1	1.5	1.4	1.9	0.9	2.2	6.0	2.8	1.5	2.1	1.6	2.3
	23.1	86.2	61.8	68.9	40	92.2	83.2	88.4	63	90	84.2	98
60 ^f	0.8	1.8	1.7	2.3	0.8	2.2	7.4	2.9	1.8	2.1	1.6	2.3
	25	88.8	73.5	88.6	46.4	92.2	92.2	88.4	77.1	90	84.2	98
360 ^e	0.9	1.8	2.0	3.0	0.9	2.2	8.2	2.9	2.2	2.1	1.6	2.3
	26.2	87.8	72.7	85.5	46.9	92.2	90	88.4	83.3	90	84.2	98
2 ppm ozone ^b	0.9	1.8	1.9	2.9	0.9	2.2	8.0	2.9	2.3	2.1	1.6	2.3
	28	48.7	37.3	29.7	51	41	11.2	31	35.5	43.2	54.1	43.2

^aReaction conditions: 25 °C and ambient pH and pressure. Abbreviations: MPPR, micropollutant percent reduction; PAR, performance advantage ratio; MPPRs listed for the 2 (200 nM)/H₂O₂ (22.4 ppm) process unless otherwise noted. PAR listed for comparison with 2 ppm ozone. ^bOzone measurements (24 h) were nonkinetic and indicate the MPPR end point concentration. ^cData from the 2 (50 nM)/H₂O₂ (22.4 ppm) system. ^dData from the 2 (200 nM)/H₂O₂ (11.2 ppm) system. ^eFigure S1. ^fFigure 1.

360 min (26–98%), signaling that 2 mostly degraded in 1 h (Figure S1).

Widely used priority MPs such as propranolol, triclosan, and trimethoprim showed MPPRs of ~84%, ~77%, and ~74%, respectively, at 6 min, compared with ozone (2 ppm) values of ~31%, ~54%, and ~43%, respectively, at 24 h. Tricloarban, diclofenac, and diltiazem could not be quantified (i.e., concentrations were below the detection level concentrations prior to and at all stages of the degradation experiments) for the 2 (200 nM)/H₂O₂ (22.4 ppm) treatment. Therefore, Table 1 includes conditions for the 2 (50 nM)/H₂O₂ (22.4 ppm) system for diclofenac and diltiazem and the 2 (200 nM)/H₂O₂ (11.2 ppm) system for tricloarban, where the MPPRs could be measured reliably. With the 2 (50 nM)/H₂O₂ (22.4 ppm) system, the EU high-priority MP diclofenac⁴⁵ gave an MPPR of 92% at 6 min that remained constant until 360 min, compared with an ozone (2 ppm) MPPR of 41%. This exceptional performance of the TAML/H₂O₂ system in removing diclofenac has also been found for 1/H₂O₂ systems deployed on London wastewater.³⁶ This equates with a 2.2-fold PAR of 2/H₂O₂ versus ozone (2 ppm) for diclofenac. Even within 30 min of operation, 2 (200 nM)/H₂O₂ (22.4 ppm) treatment provided PARs (vs 2 ppm ozone) for green zone MPs ranging between 0.8 and 7.4 and this increased to 0.9–8.2 after operation for 60 min and remained mostly unchanged beyond that (Table 1). The significance of this performance is evident in the context that Switzerland's Neugut showcase plant in Dübendorf utilizes 1.6–2.7 ppm for MP treatment.¹⁶ While ozone clearly outperforms 2/H₂O₂, under the TAML process conditions studied at 6–8 ppm, treatment with higher ozone concentrations adds additional costs and post-treatment requirements.

The 1 h data (Figure 2; Figure S1 for other times) with the 2 concentration set at either 200 or 100 nM show little difference when the H₂O₂ concentration ([H₂O₂]) is set at either 22.4 or 11.2 ppm, meaning the peroxide concentration is satisfactory at ≥11.2 ppm and possibly lower. The 2/H₂O₂ heat maps change insignificantly between 1 and 6 h (Figure 2 and Figure S1), indicating that 2 was mostly deactivated after 1 h. An active "kill switch" in the form of an acidic C(Me)–H group bridging the two sulfonamido groups dominates the degradation chemistry of 2.¹⁹ Although the kill switch penalizes the technical performance, it permits process conditions to be tightly controlled to ensure the catalyst is fully degraded before the release of treated waters to lakes or rivers. This reduces environmental performance concerns of active catalyst toxicity; 2 is currently undergoing extensive low-dose/concentration toxicity testing (zebrafish, mouse, and frog) as part of Sudoc, LLC (www.sudoc.com), commercial development of this catalyst for multiple applications. When the kill switch is turned off in a modified catalyst in development, the technical performance of the TAML/H₂O₂ system can be confidently projected to improve significantly, decreasing catalyst requirements for achieving the same MPPRs. However, this still requires an investigative balancing of technical, cost, and environmental performances, prioritizing the last.

Both older- and latest-generation TAMLs are known to be so effective at activating H₂O₂ to remove estrogens^{25,26,36} and phenols³³ in general, including from MWWTP effluent,³⁶ that estrogen assays were not conducted; this effectiveness against phenols was recently reinforced by a study in an independent laboratory.⁴⁶ Previously, prepubertal mouse uterotrophic assays have shown that pretreatment of water containing the

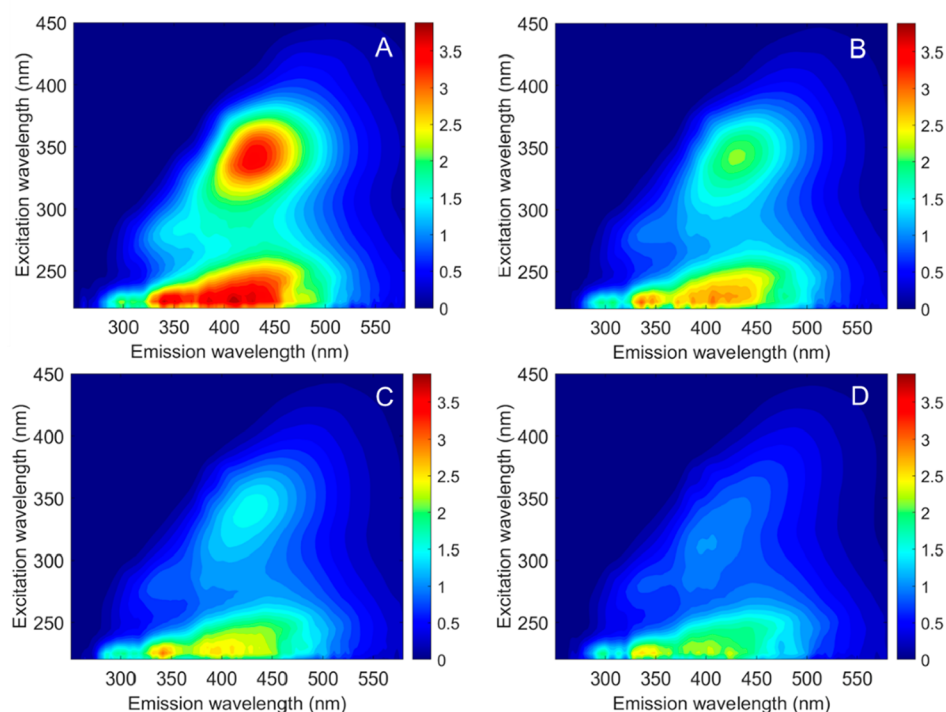


Figure 3. Three-dimensional excitation–emission fluorescence spectra with fluorescence intensity dimension in color (relative fluorescence units) of Tucson Agua Nueva MWWTP secondary wastewater after treatment for 6 h with H_2O_2 (22.4 ppm) and **2**: (A) 0 nM, (B) 50 nM, (C) 100 nM, and (D) 200 nM. Reaction conditions: ambient pH, 25 °C, and ambient pressure. All data points are averages of three experiments.

synthetic estrogen ethinylestradiol (EE2) with a latest-generation ultradilute TAML (4 and 40 nM)/ H_2O_2 system blocks the induced increase in uterine weight that accompanies low-dose EE2 exposures, indicating effective breakdown of EE2. Histopathological and uterotrophic assays of different cohorts of mice exposed to TAML, EE2, and degraded EE2 showed no low-dose toxicity for a close relative of **2**.¹⁹

3.2. Oxidation of the Wastewater Organic Matrix: Excitation–Emission Matrix (EEM) Plots. MPs in municipal wastewater are part of a larger pool of organic matter that has passed through the various treatment stages of the plant and can also be expected to compete with the MPs for the active intermediate AC (Figure 1). Therefore, the collective response of the wastewater organic matrix to different **2**/ H_2O_2 treatments was evaluated by three-dimensional plots of excitation, emission, and fluorescence intensity to characterize the different types of fluorophores and their changing concentrations under **2**/ H_2O_2 treatment. Excitation–emission pairs are characteristic of each type of fluorophore, and there are five operational ultraviolet (UV)–visible regional boundaries for calculating the total fluorescence (TF) of wastewater (Table S4).^{47,48} There were three maxima in the Tucson water control spectrum as is typically found⁴⁹ (Figure 3A): (i) excitation at \sim 230 nm and emission at 340 nm (tryptophan containing aromatic proteins), (ii) excitation at \sim 230 nm and emission at 420 nm (hydrophobic fulvic acid-like compounds), and (iii) excitation at \sim 340 nm and emission at 420 nm (hydrophobic humic acid-like matter). At 22.4 ppm H_2O_2 , in reference to the control (**2**, 0 nM), treatment with 50, 100, and 200 nM **2** produced decreases in total fluorescence (TF) of 23.3%, 30.8%, and 40.3%, respectively (Figure 3B–D and Table S5). Treatment with **2** (200 nM) and H_2O_2 (22.4 ppm) showed decreases of 34%, 39.6%, and 54% in regions II, III, and V, respectively, indicating **2** with H_2O_2 is most effective in

oxidizing humic acid-like matter (region V, Figure 3D). As with the TF, the UV 254 nm wastewater absorbance also showed an overall decrease after **2**/ H_2O_2 treatment. With H_2O_2 (22.4 ppm), 50, 100, and 200 nM **2** produced 10.9%, 14.3%, and 17.7% decreases in UV 254 absorbance, respectively (Figure S2), from an initial absorbance of 0.145 for **2** (0 nM) with H_2O_2 (22.4 ppm).

Combining the superior performance of our TAML/ H_2O_2 system against industrially relevant 2 ppm ozone (PARs shown in Table 1) leads us down the path of needing to show that the costs of catalyst production and peroxide management are workable, in which case TAML/ H_2O_2 could provide an efficient and economical alternative to ozone treatment. With its simple mixing of two reagent solutions into water under ambient conditions, TAML/ H_2O_2 seems much easier to deploy than ozone, the technology receiving the most attention for MP abatement. The simplicity should positively impact comparative cost performances in favor of TAML/ H_2O_2 over ozone. For plants with \leq 50,000 population equivalents, where ozone costs per capita increase quickly with decreasing population bases, the costs of TAML/ H_2O_2 per capita are expected to be nearly independent of the population size. The key cost determinant will be TAML costs at scale. Thus far, we have produced the prototype TAML catalyst in 100 kg batches from which we deduce a high probability that TAML/ H_2O_2 will have considerably lower operating costs than ozone. However, this optimistic projection must be confirmed or disproven by building and operating a TAML/ H_2O_2 demonstration plant, including finding that the technology is sustainable from studies of the health of the receiving waters before and after treatment.

3.3. Kinetics of $\text{2/H}_2\text{O}_2$ Treatments: Trimethoprim as a Case Example. Trimethoprim is a World Health Organization (WHO) Essential Medicine commonly used as

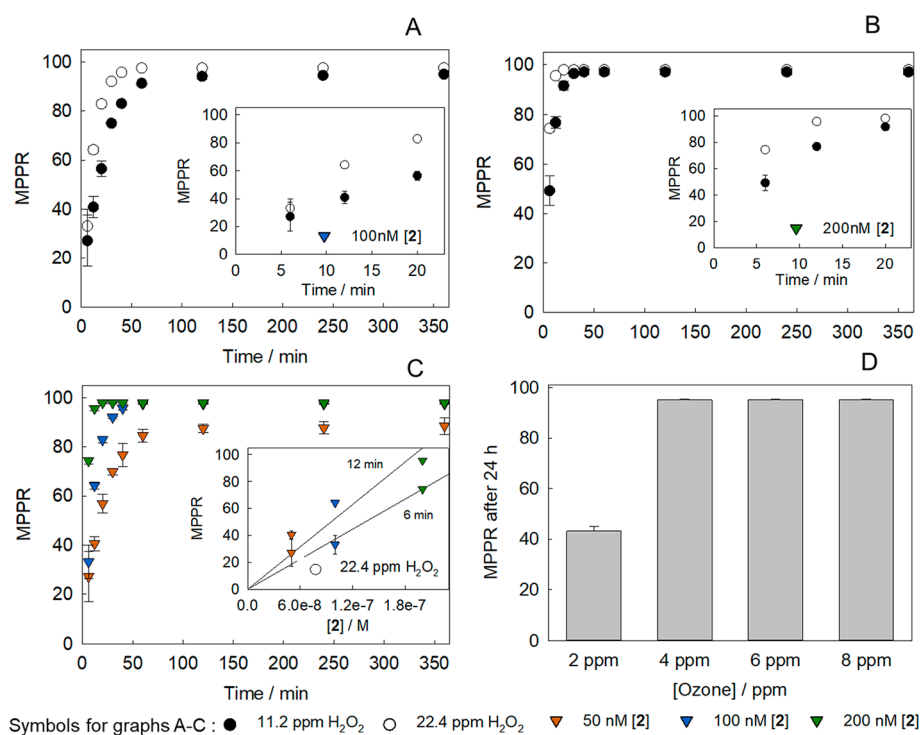


Figure 4. MPPRs (micropollutant percent reductions) for trimethoprim (6 h) for 2/H₂O₂ treatments: (A) 2 [100 nM (blue triangles)] and H₂O₂ [11.2 or 22.4 ppm (black or white circles, respectively)], (B) 2 [200 nM (green triangles)] and H₂O₂ [11.2 or 22.4 ppm (black or white circles, respectively)], (C) 2 [50, 100, or 200 nM (brown, blue, or green triangles, respectively)] and H₂O₂ [22.4 ppm (white circles)], and (D) 2, 4, 6, and 8 ppm ozone treatments (24 h end point value). The insets of panels A and B show changing MPPRs over the first 20 min. The inset of panel C shows MPPR at 6 and 12 min for 2 [50, 100, or 200 nM (brown, blue, or green triangles, respectively)] and H₂O₂ [22.4 ppm (white circles)]. Averages of triplicate experiments. Reaction conditions: 25 °C and ambient pH and pressure.

an antibiotic for bladder infections and for pneumonia in HIV-infected patients and is the most commonly found and highest-concentration antibiotic contaminant in selected rivers worldwide.⁵⁰ Trimethoprim could be measured across various treatments (for all time points, see Figure 4) and had the highest MPPRs. Thus, it was chosen for illustrative kinetic analyses aimed at probing if 2/H₂O₂ exhibits typical TAML kinetic properties and features in these systems.

Kinetic analyses were performed with trimethoprim as the substrate for all following combinations of 2 and H₂O₂: 50, 100, and 200 nM 2 and 11.2 ppm (0.33 mM) and 22.4 ppm (0.66 mM) H₂O₂. The results are presented in Figure 4. For each concentration of 2, the MPPR was found to increase with the concentration of H₂O₂, in accordance with the commonly found rate equation for TAML catalysis shown in Figure 1. With 100 nM 2, maximum MPPRs for 11.2 (0.33 mM) and 22.4 (0.66 mM) ppm H₂O₂ occur at 60 and 30 min, respectively (Figure 4A), whereas maximum MPPRs with 200 nM 2 occur at 30 and 20 min, respectively (Figure 4B). For any given concentrations of 2 and H₂O₂, the MPPR initially increases linearly with time and begins curving and flattening as the maximum MPPR gets closer (insets of panels A and B of Figure 4). Remarkably, after treatment for only 12 min, at 200 nM 2 MPPR values of 77% and 96% were achieved with 11.2 (0.33 mM) and 22.4 (0.66 mM) ppm H₂O₂, respectively (inset of Figure 4B).

Ozone MPPRs were explored at 2, 4, 6, and 8 ppm ozone. At 6 and 8 ppm, ozone performed very well compared to 2 and 4 ppm ozone and all 2/H₂O₂ conditions in greening the amber zone while improving green zone MPPRs (Figures S1 and S3 and Table S6). After treatment for 6 h, the highest-

performance 2 (200 nM)/H₂O₂ (22.4 ppm) system provided the following MPPR values for amber zone MPs: TCEP (41), TCPP (17.2), atenolol (12.7), sucralose (4.38), iohexol (14.1), iopamidol (6.8), iopromide (5.07), meprobamate (15), acesulfame (10), primidone (4.43), fluoxetine (21), gabapentin (2.96), benzophenone (−41), and benzotriazole (14.2). In contrast, 8 ppm ozone MPPRs (after 24 h) were as follows: TCEP (−6.4), TCPP (7.6), atenolol (NA), sucralose (33.6), iohexol (51), iopamidol (47.7), iopromide (49.7), meprobamate (54.9), acesulfame (72.3), primidone (75.5), fluoxetine (NA), gabapentin (71.5), benzophenone (56), and benzotriazole (91.3).

Trimethoprim removal exhibits an expected first-order relationship in 2 (inset of Figure 4C) based on the TAML catalysis mechanism (eq 1, Figure 1). Only the 6 and 12 min data are shown here because the MPPR is already ~90% at 12 min for 200 nM 2. At 22.4 ppm H₂O₂ and 50, 100, or 200 nM 2, the maximum MPPRs were achieved at ~120, 60, and 20 min, respectively, with values of ~84%, ~98%, and ~98%, respectively. Remarkably, even at only 6 min with 22.4 ppm H₂O₂ and 50, 100, and 200 nM 2, MPPRs of 28%, 33%, and 74%, respectively, were achieved. The 2 concentration dependencies for green zone MPs at 22.4 ppm H₂O₂ are shown for the first 6 min in Figure S4. Once MP oxidized intermediates have been formed, they compete with the parent MPs for the active form of 2. For the seven compounds shown in Figure S4, everything except triclosan exhibited a linear dependency on the concentration of 2 (eq 1, Figure 1), with R² varying from 0.95 to 0.98. It is important to note again that some activated 2 is also being consumed continuously in oxidizing the wastewater organic matrix (Figure 3).

Do the above results make the 2/H₂O₂ system suitable for reduction of MP release at MWWTPs? And if so, what scale of adoption is reasonable to project? These questions can be considered through the lens of the sustainability performances we have defined: technical, cost, health, environmental, and fairness.¹⁹ Considering the data presented in this paper, were we to begin a 2-based plant pilot trial tomorrow aiming to match ozone at 3 ppm, we would start with 70 nM 2 and 11.2 ppm H₂O₂, seeking the lowest viable peroxide concentration (≤ 10 ppm) (see all results in Figure 2 and Figure S1). This translates to starting the optimization under conditions that equate with treating the daily output of 150,000 Europeans (averaging 150 L/day, 22,500 tons total) with 1 kg of 2 and 253 kg of H₂O₂ for 30 min to 1 h. On technical performance, a single 2/H₂O₂ treatment clearly rivals ozone up to 3.5 ppm in MP removals. As discussed above, the simplicity of the TAML/H₂O₂ treatment and its independence of per capita cost from population size favor the TAML/H₂O₂ system over ozone, especially in plants with $\leq 50,000$ pE. At the current state of development, the fairness performance of the TAML/H₂O₂ system likely is inherently higher than that of ozone because it should be easily viable in smaller communities ($\leq 50,000$) and poorer jurisdictions. Because the TAML/peroxide system quickly removes estrogens that are particularly toxic to aquatic life, it might be that the initial commercial development will arise from rapid removal of estrogens and other green zone MPs to significantly improve the wastewater quality of smaller plants. As it appears to us today, the most important questions for TAML/H₂O₂ viability at MWWTPs concern environmental performance. Despite impressive evidence of the absence of low-dose and concentration adverse effects for TAMLs, environmental safety questions can only be put to rest by studies of the receiving waters of a full demonstration plant and, in our judgment, by expanded tests for endocrine disruption regardless of whether they are required by regulatory agencies. For now, while the health performance projections look excellent from existing safety studies, drinking water treatment studies are on hold until the technology is backed by considerable wastewater experience and real-world process safety studies satisfy regulatory bodies and us on the issues surrounding endocrine disruption and other low-dose and -concentration toxicities.

4. CONCLUSION

The latest-generation TAML, 2, catalytically activates hydrogen peroxide giving an efficient, easy-to-deploy approach for purifying wastewater of MPs. At Tucson's Agua Nueva Water Reclamation Facility, the highest-performance treatment, 2 (200 nM) with H₂O₂ (22.4 ppm), performs better than 2 ppm ozone (used in a WWTP in Switzerland)¹⁶ for most MPs. For the substantially removed green zone MPs, 2 (200 nM) and H₂O₂ (22.4 ppm = 0.66 mM) show PARs versus 2 ppm ozone ranging from 0.9 to 8.0. Total fluorescence (TF) measurements, through EEM plots, indicated that the organic matrix is oxidized with a maximum TF reduction of 40% for the 2 (200 nM)/H₂O₂ (22.4 ppm) treatment. Within the organic matrix, humic acid-like substances were oxidized the most, leading to a 54% reduction in TF. A detailed kinetic analysis of the 2/H₂O₂ degradation of trimethoprim has showcased that this ultra-dilute process adheres to the typical TAML mechanism described in Figure 1. For green zone MPs, kinetic studies reveal an almost linear dependence of the MPPR on 2 concentration. For the same 2 concentration, MPPRs were

found to be roughly similar for treatment with 22.4 ppm H₂O₂ and treatment with 11.2 ppm H₂O₂. As expected, higher MPPRs were observed for ozone at 6 and 8 ppm compared with ozone at 2 and 4 ppm.

The results of this study show that the 2/H₂O₂ system is an already powerful technical solution for MP abatement in municipal wastewater. In other work, the cost and environmental performances are being examined. The methodology is still advancing through iterative catalyst design. As a final note, a medium-range activity earlier-generation TAML has been shown to enable a remarkably simple approach to the disinfection of bacterial spores, the hardest microbes to kill.²⁸ The latest generation of TAMLs is expected to provide an even more powerful disinfection technology.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsestwater.1c00213>.

Tables summarizing micropollutants, categorized by their primary utility; ESI-MS and instrumental parameters; regional fluorescence integration boundaries and their percent decrease post-treatment; figures that show MPPR kinetics for 2/H₂O₂ treatments; UV 254 absorbance of wastewater; ozone MPPRs; and dependence of MPPRs on the 2 concentration (PDF)

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Author Contributions

Y.S., G.R.W., and T.J.C. are co-inventors of the latest generation of TAML activators. G.R.W. synthesized 2. Y.S. and M.P. performed the wastewater experiments. K.D.D. and M.P. performed the analytical measurements. Y.S. performed the extensive data analysis with input from T.J.C., M.P., and K.D.D. A.D.R. provided advice on kinetics. Y.S. and T.J.C. primarily wrote the manuscript with input from all authors.

Notes

The authors declare the following competing financial interest(s): T.J.C., Y.S., and G.R.W. are co-inventors on a patent and patent applications for the latest-generation TAMLs. T.J.C. is a co-founder of Sudoc, LLC, which is developing applications of the new catalysts, including municipal wastewater treatment.

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