

Fenton Chemistry for Achmatowicz Rearrangement

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ABSTRACT: Achmatowicz rearrangement (AchR) is a very important transformation for the synthesis of various heterocyclic building blocks and natural products. Here, the discovery of Fenton chemistry for AchR using a bifunctional catalyst (FeBr₂ or CeBr₃), which has environmental friendliness and a broad substrate scope at the same time has been reported. This method addresses the major limitation of conventional chemical (hazardous) and enzymatic (limited scope) methods. Mechanistic studies suggested AchR and that Fenton chemistry [Fe/Ce (cat.) + H₂O₂ \rightarrow HO[•]/RBS. Importantly, this in situ RBS generation from M-Br_x-H₂O₂ many haloperoxidase mimics that require a strong acidic additio opportunities for many other brominium-mediated organic reaction



enzymatic (limited scope) methods. Mechanistic studies suggested that reactive brominating species (RBS) is the true catalyst for AchR and that Fenton chemistry [Fe/Ce (cat.) + $H_2O_2 \rightarrow HO^{\bullet}/HOO^{\bullet} + H_2O$] is responsible for the oxidation of bromide into RBS. Importantly, this in situ RBS generation from M-Br_x-H₂O₂ under neutral conditions addresses the long-lasting problem of many haloperoxidase mimics that require a strong acidic additive/medium for bromide oxidation with H₂O₂, which creates opportunities for many other brominium-mediated organic reactions.

KEYWORDS: fenton chemistry, Achmatowicz rearrangement, green chemistry, hydrogen peroxide, haloperoxidase mimics

chmatowicz rearrangement (AchR) is a very important A reaction for the construction of six-membered heterocyclic scaffolds (dihydropyranones and dihydropyridinones), which are frequently found in bioactive molecules and natural products.¹ The synthetic utility of AchR has been illustrated by various transformations of AchR products,² including Oglycosylation,³ [5 + 2] cycloaddition,⁴ Kishi reduction,⁵ Ferrier allylation,⁶ ketalization,⁷ redox isomerization,⁸ and Tsuji-Trost arylation⁹ (Figure 1a). The importance of AchR in organic synthesis aroused great interest in developing new and more efficient oxidation protocols, which can be classified into chemical¹⁰ and enzymatic strategies¹¹ (Figure 1b). The chemical strategy employs stoichiometric strong oxidants such as m-CPBA^{10m} and N-bromosuccinimide (NBS),¹⁰ⁿ which are toxic and result in stoichiometric harmful byproducts (i.e., *m*-chlorobenzoic acid or succinimide). Recently, our group reported oxone-KBr¹² as a green catalytic protocol for AchR. However, as compared to oxygen and hydrogen peroxide, oxone as a terminal oxidant was not ideal and the *E*-factor¹³ was usually high because of high molar mass (307 g/mol) of oxone (molar mass of H₂O₂ and O₂: 34 and 32 g/mol, respectively). Photochemical oxidation with singlet oxygen reported by Vassilikogiannakis^{10p,10g} was another green method for AchR, but it requires stoichiometric reducing agents (Me₂S or Ph₃P). Anodic oxidation/rearrangement (2 steps) as the greenest protocol was reported in 1976^{10h} but with only three examples and moderate yields (37-73%). The enzymatic strategy reported recently by Beifuss,^{11b} Deska (2014; 2018),^{11c11a} and Hollmann and Rutjes^{11e} uses hydrogen peroxide as the stoichiometric terminal oxidant and produces water as the only byproduct. Enzymatic protocols are green but suffer from a narrow scope (<10 examples

illustrated) and a low reaction concentration (mM). Herein, we report the discovery of Fenton chemistry for AchR with H_2O_2 as the terminal oxidant, which is not only green but also has a wide scope under a normal concentration (0.2–0.5 M) for organic reactions.

Fenton chemistry (Fe^{II}/H_2O_2) is widely used for contaminant or wastewater treatment¹⁴ because (i) Fenton chemistry has low cost, negligible toxicity, and easy recovery and a (ii) hydroxyl radical (•OH) generated from Fenton chemistry (Figure 2a) is a highly strong oxidant¹⁵ that can degrade most organic pollutants into nontoxic oxidized small molecules.¹⁶ Many iron catalysts have been developed¹⁷ and the Fenton process can be advantageously performed in many physical fields.^{14,18,19}

Fenton chemistry has also been used in organic synthesis for many oxidation reactions. For example, $[Fe^{II}]/H_2O_2$ was used for C–H oxidation [Gif oxidation, Figure 2b(3)],²⁰ Minisci reaction [Figure 2b(4)],²¹ sulfide oxidation [Figure 2b(5)],²² and olefin oxidation [Figure 2b(6)].²³ Notably, well-designed organic ligands²⁴ for iron are typically required to tune the oxidation reactivity and selectivity, especially in an olefin epoxidation reaction.²⁵ Nevetheless, the synthetic utility of Fenton chemistry in organic synthesis remains very limited due to poor chemoselectivity of the highly oxidizing hydroxyl radical. Our continuous interest in AchR drove us to upgrade

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Figure 1. Synthetic utilities of AchR, previous strategies for AchR, and our catalytic protocol.

our previous oxone-halide system and envisioned that Fenton chemistry might be used for AchR [Figure 2c(c1)] through epoxidation analogous to the equation (6) [Figure 2b(6)].²⁵ Alternatively, Fenton chemistry may oxidize a bromide ion into reactive brominating species (RBS; Br⁺) for AchR [Figure 2c(c2)], which is similar to NBS and oxone-KBr for AchR. If successful, it would be the first example of Fenton chemistry for AchR with H₂O as the only waste product [Figure 2c(7)] and greener than our previous oxone-KBr protocol.

Because other transition metals such as chromium, cerium, copper, cobalt, manganese, ruthenium, and aluminum had been used for decomposition of H2O2 into OH and were classified as iron-free Fenton-like catalysts,²⁶ we started our study with a nonselective screening of transition-metal salts including lanthanides for oxidation of furfuryl alcohol (1a) with hydrogen peroxide. Disappointingly, no reaction occurred, which suggested that Fenton chemistry did not work for AchR through the epoxidation pathway. However, when 0.1 equiv of KBr was added to the reaction, we were pleased to find that 16 out of 38 transition-metal salts showed a positive result and delivered >5% yield of dihydropyranone (2a) in nearly neutral conditions (Table 1). This finding suggested KBr was mechanistically involved in the AchR and the Fenton chemistry (Fe^{II}/H_2O_2) served as an oxidant for bromide oxidation, which may follow the bromination hypothetic pathway [Figure 2c(c2)].

This initial finding was significant because it suggested that the oxidation of bromide with H_2O_2 could occur under neutral

conditions without an enzyme (haloperoxidase or halogenase) or a strong acid (AcOH, HBr, H_2SO_4 , or HClO₄ was required for haloperoxidase mimics).²⁷ Remarkably, seven metal salts, FeCl₂, CeCl₃, Sc(OTf)₃, Cp₂ZrCl₂, SnCl₂, Eu(OTf)₃, and Tm(ClO₄)₃, were found to be efficient catalysts (>40% yield, the detailed information is provided in the Supporting Information) under this unoptimized condition (Table 1). Nevertheless, the yield was not high or synthetically useful yet and needed to be further optimized. Since it was impractical to simultaneously investigate all of these seven promising metal salts for the yield improvement, we focused on iron and cerium for further optimization because of their nontoxicity, low cost, and environmental friendliness.

The optimization campaign was launched, and the corresponding results are presented in Table 2. The standard experiment employed 0.1 equiv of a metal catalyst and we aimed for >70% yield to verify the good catalytic activity. Interestingly, we observed that the organic ligands such as acetylacetone (acac), porphyrin, cyclopentadiene (Cp), and CO (entry 1–5, Table 2) were inferior to inorganic ligands such as sulfate, nitrate, and chloride (entry 6–8, Table 2). The best yield (78% for iron and 91% for cerium) was obtained with catalytic FeBr₂ (entry 11) and CeBr₃ (entry 16), in which bromide (Br⁻) was not only the ligand of iron and cerium but also the source of reactive brominating species (RBS) for AchR. Notably, the reaction using FeBr₂ or CeBr₃ as a catalyst was completed within 2 h, which was faster than the other combinations (metal salt + KBr).

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Figure 2. Fenton chemistry and its synthetic utilities in organic synthesis, and our mechanistic hypothesis for AchR through Fenton chemistry.

With the discovery and optimized condition $(FeBr_2-H_2O_2)$ and $CeBr_3-H_2O_2$) in hand, we set out to examine and expand the scope of furfuryl alcohol for AchR (Table 3a). It was noteworthy that some substrates (2a, 2e, 2n, 2q, etc.) were chosen according to our published literatures¹² using the oxone-KBr protocol to make a systematic green chemistry metrics comparison with this M-Br_x-H₂O₂ protocol. To our delight, the oxidative rearrangement proceeded with high efficiency for a variety of furfuryl alcohols under this catalytic neutral condition. The mild reaction conditions tolerated common functional groups such as ester (2g and 2w), alkene (2e and 2t), electron-rich arenes (2o-2r), and furan/ thiophene (2x and 2y), commonly used protecting groups like triisopropylsilyl (TIPS) (2p and 2aa), *tert*-butyldimethylsilyl (TBS) (2l and 2r), Bn (2i and 2v), Ac (2o and 2u), Bz (2h), Piv (2k), and Boc (2j), unusual substituents on 3- and/ or 4-position of furan (2z-2ac), and sterically hindered furfuryl tertiary alcohols (2m and 2n). The scalability of these two catalytic methods was demonstrated by a 10 mmol scale reaction of 2b ($R_1 = t$ -Bu, 1.54 g) at room temperature under an open-air condition, which gave excellent yields (FeBr₂: 77%; CeBr₃: 92%) comparable to the yields of 0.4 mmol scale (81 and 93%, respectively). It was noted that a relatively lower catalyst loading was needed for CeBr₃ (0.03 equiv) vs FeBr₂ (0.15 equiv), which means that CeBr₃ is more efficient than FeBr₂ for the large-scale synthesis. Furthermore, there were no potentially competing side reactions like arene bromination, alkene dibromination, and alcohol oxidation for the above substrates. Interestingly, the more hydrophobic substrates always gave a higher yield. Consequently, our Fenton protocol Table 1. Nonselective Screening of a Metal Catalyst for AchR for 1a Using H_2O_2 as an Oxidant^a



^{*a*}Reaction was carried out at rt: **1a** (0.1 mmol) was dissolved in a solvent (tetrahydrofuran (THF)/H₂O 10/1, 0.55 mL), and then transition-metal salt (0.01 mmol), KBr (0.01 mmol), and H₂O₂ (30%, 22 μ L, 0.22 mmol) were added and stirred at rt for 8 h. The reaction was quenched using a dilute Na₂S₂O₃ aqueous solution. The detailed procedure is given in the Supporting Information.

	1		
6	[M] (0.1 eq) OH KBr (0.1 eq) H ₂ O ₂ (2.2 eq)		<u>-</u> 0
//	<u>/</u>	HOwo	∕ <i>i-</i> Pr
	1a	2a	
entry ^a	MXn (0.1 equiv) + KBr (0.1 equiv)	solvent	yield ^d (%)
1	Ferroceneacetic acid + KBr	THF/H ₂ O	<5
2 ^b	$Cp_2Fe_2(CO)_4 + KBr$	THF/H_2O	<5
3	$Fe(acac)_3 + KBr$	THF/H_2O	<5
4 ^b	$\mathbf{Fe}_2(\mathrm{CO})_9 + \mathbf{KBr}$	THF/H_2O	<5
5	Heme B + KBr	THF/H_2O	<5
6	$Fe(NO_3)_3 + KBr$	THF/H_2O	37
7	$FeSO_4 + KBr$	THF/H_2O	30
8	$\mathbf{FeCl}_3 + \mathbf{KBr}$	THF/H_2O	58
9	FeBr ₂	$MeCN/H_2O$	68
10	FeBr ₂	DMF/H ₂ O	30
11 ^c	FeBr ₂	THF/H_2O	78
12 ^b	$\mathbf{Ce}_2(\mathbf{C}_2\mathbf{O}_4)_3 + \mathbf{KBr}$	THF/H_2O	61
13	$Ce(NO_3)_3 + KBr$	THF/H_2O	80
14	$Ce(SO_4)_2 + KBr$	THF/H_2O	81
15	$CeCl_3 + KBr$	THF/H_2O	77
16 ^c	CeBr ₃	THF/H ₂ O	91

Table 2. Optimization of AchR for 1a

^{*a*}Reaction was carried out at rt: **1a** (0.1 mmol) was dissolved in a solvent (organic solvent/H₂O 10/1, 0.55 mL), and then [Fe] or [Ce] (0.01 mmol), KBr (0.01 mmol), and H₂O₂ (30%, 22 μ L, 0.22 mmol) were added and stirred at rt for 8 h. The reaction was quenched using a dilute Na₂S₂O₃ aqueous solution. ^{*b*}Metal catalyst (0.005 mmol) was added. ^{*c*}Reaction time was 2 h. ^{*d*}Yield was determined by ¹H NMR analysis of the crude reaction mixture using CH₂Br₂ as the internal reference.

 $(FeBr_2/H_2O_2 \text{ and } CeBr_3/H_2O_2)$ holds great promise for commercialization and medicinal chemistry with the following advantages: (1) H_2O_2 as the green oxidant, (2) low-toxic catalyst (FeBr₂ and CeBr₃), (3) scalable operation without special equipment, (4) very mild condition (RT), and (5) a wide substrate scope with high yields and tolerence of multiple functional groups.

To evaluate the greenness of our new system and make a comparison with our previous oxone-halide protocol, we chose AchR of furfuryl alcohols to 2a, 2e, 2n, and 2q as representative examples to analyze their green chemistry metrics. We performed the calculation of four green metrics, environmental factor (*E*-factor),¹³ atom economy (AE),²⁸ reaction mass efficiency (RME),²⁹ and process mass intensity (PMI),³⁰ for FeBr₂-H₂O₂, CeBr₃-H₂O₂, and oxone-KBr (Table 3b). The lower value of the *E*-factor (ideal: 0.00) and PMI (ideal: 1.0) means that less waste is generated or less total mass of material is needed for per mass of the desired product,^{13,30} while the higher value of AE (ideal: 100%) and RME (100%) reveals better atom and resource efficiency.^{28,29} As shown in Table 3b, the average E-factors of AchR using oxone-KBr, FeBr₂-H₂O₂, and CeBr₃-H₂O₂ were 5.46, 0.98, and 0.69, respectively, which suggested that $M-Br_x-H_2O_2$ could be reduced six to eight times of mass waste than oxone-KBr and was closely approaching to the ideal metrics (E-factor: 0.00). The average AE value of $FeBr_2-H_2O_2$ and CeBr₃-H₂O₂ was 91.2%, which suggested more than 50% increase from 39.9% for oxone-KBr. The average 60% RME of M-Br_x $-H_2O_2$ indicated the reaction's mass advantage over oxone-KBr (RME: 16.8%). Finally, the PMI value ratio of oxone-KBr (PMI: 6.46) and M-Br,-H₂O₂ (PMI: ~1.8) was \sim 3.5, which means nearly 4-fold materials were needed using the oxone-KBr method. The analysis of these green metrics clearly demonstrated that our new M-Br_x-H₂O₂ was greener, more efficient, and environmentally friendly (sustainable) than our previous oxone-KBr and other existing approaches. It was noteworthy that oxone was synthesized industrially from H_2O_2 in two steps (first concentrated H_2SO_4 and then KOH).³¹ Taking this fact and the stoichiometric waste generated into consideration, our new M-Br_r-H₂O₂ method was greener and should be preferably used over the oxone–KBr protocol (H₂O vs $K_2SO_4 + Na_2SO_4 + CO_2$).

To shed light on the mechanism of Fenton chemistry for AchR, we designed and performed a series of controlled experiments and characterizations of AchR (Figure 3). First, controlled experiments (Figure 3a) were divided into two sets (S-1 and S-2); S-1 was designed to investigate the role of metal and bromide (Figure 3a, entries 1–17). It was found that both metal (Fe²⁺ or Ce³⁺) and bromide were indispensable for AchR, which suggested that (1) RBS was generated from the reaction of M-Br (FeBr₂ or CeBr₃) and H₂O₂ and served as the

Table 3. Fenton Chemistry for Achmatowicz Rearrangement^a



^{*a*}Reaction conditions for AchR: furfuryl alcohol (0.4 mmol), FeBr₂ (0.1 equiv) or CeBr₃ (0.08 equiv), H₂O₂ (2.2 equiv), THF/H₂O (10/1, 2.2 mL), and room temperature for 2–3 h. ^{*b*}FeBr₂ (0.2 equiv) and H₂O₂ (4.4 equiv) were needed. 'Yield obtained from 1.54 g of 1b using FeBr₂ (0.15 equiv) or CeBr₃ (0.03 equiv).

active catalyst for AchR, and (2) without a bromide ion, Fenton chemistry (FeSO₄–H₂O₂)^{14,32} could not affect AchR (Figure 3a, entries, 2, 4, 6, 8, 10, 12, 14, and 16). The second set (S-2) of controlled experiments (Figure 3a, entries 18–25) was designed to explore the possible presence of a hydroxyl radical (HO[•])³³ from Fenton chemistry. ABTS³⁴ [2,2'-Azinobis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt] as a Fenton scavenger was added to the AchR reaction promoted by FeBr₂–H₂O₂ (entries 18–19), CeBr₃–H₂O₂³⁵

(entries 20–21), *m*-CPBA (entries 22–23), and oxone–KBr (entries 24–25). Clearly, only FeBr₂–H₂O₂ and CeBr₃–H₂O₂ were significantly suppressed by ABTS, which suggested that they involved the hydroxyl radical (HO[•]). To further support the generation of the hydroxyl radical (HO[•]), we recorded the UV–visible spectra for the reaction of M-Br (FeBr₂ or CeBr₃) and H₂O₂ in the presence of ABTS ($\lambda_{max} = 340$ nm) (Figure 3b). Chromagen ABTS³⁵ ($\lambda_{max} = 340$ nm) was widely used to trap the short-lived hydroxyl radical, and the resulting cation



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Figure 3. Mechanistic studies and hypothesis. (a) RBS-promoted AchR and the presence of a hydroxyl radical from Fenton chemistry. For the first set, light blue bars represent the controls using either M or Br, while the orange ones use both M and Br. Compared with the green bars in set 2, the red ones represent the controls with the addition of ABTS to trap the hydroxyl radical. Note: 5% yield was used in the chart for the yields lower than 5%. (b) UV–vis spectral experiments with ABTS to confirm the generation of the hydroxyl radical. (c) Br⁺-trapping experiment by the intramolecular bromocyclization of alkenyl carboxylic acid **3** and bromination of arene **5** using FeBr₂–H₂O₂ or CeBr₃–H₂O₂. (d) Proposed mechanism for generation of bromide with the fleeting hydroxyl radical. (f) Proposed mechanism for catalytic oxidation of furans.

radical ABTS^{+•34} ($\lambda_{max} = 415$ nm) was far more stable and could be characterized by UV–visible spectroscopy. It was observed that absorbance of ABTS^{+•} at 415 nm increased with increasing concentration of FeBr₂ and CeBr₃, which corroborated the generation of the hydroxyl radical (HO[•]) from FeBr₂–H₂O₂ and CeBr₃–H₂O₂ (Figure 3b). It was interesting to note that the absorbance of ABTS^{+•} at 415 nm in a CeBr₃– H₂O₂ solution was considerably lower than that in a FeBr₂– H₂O₂ solution. This difference might suggest that the generation of the hydroxyl radical (HO[•]) from CeBr₃–H₂O₂ was slower than that from FeBr₂–H₂O₂. The slow release of the fleeting hydroxyl radical (HO[•])^{33,36} from the CeBr₃–H₂O₂ solution might well explain our observation that CeBr₃–H₂O₂ generally outperformed the FeBr₂–H₂O₂ system in the AchR (Table 3).

To further support the generation of RBS from $\text{FeBr}_2-\text{H}_2\text{O}_2$ and $\text{CeBr}_3-\text{H}_2\text{O}_2$, we performed two oxidative bromination, as shown in Figure 3c. Bromolactonization of alkenyl carboxylic acid **3** using $\text{FeBr}_2-\text{H}_2\text{O}_2$ or $\text{CeBr}_3-\text{H}_2\text{O}_2$ in acetonitrile provided lactone **4** in 53 and 62% yields, respectively. Bromination of TBS-protected phenol (**5**) with $\text{FeBr}_3-\text{H}_2\text{O}_2$ and $\text{CeBr}_3-\text{H}_2\text{O}_2$ gave TBS-protected 4-bromophenol (**6**) in high yields (FeBr_2 :76%; CeBr_3 :94%). These experiments conclusively confirmed the generation of RBS ([Br^+]) from $\text{FeBr}_2-\text{H}_2\text{O}_2$ and $\text{CeBr}_3-\text{H}_2\text{O}_2$.

According to these mechanistic studies, we proposed a plausible mechanism for AchR (Figure 3d-f). Fenton chemistry occurred to generate a hydroxyl radical and/or a hydroperoxyl radical (HOO[•]) as a strong oxidant, which can oxidize a bromide ion into hypobromous acid $(HO-Br)^{37}$ as the RBS for various oxidations (Figure 3d). To account for this observation that FeBr₂ and CeBr₃ were consistently more efficient than the corresponding combination of metal salts and potassium bromide (i.e., $FeSO_4 + KBr$, $Ce(OAc)_3 + KBr$ in Table 2), we proposed the concept of an ion-radical pair: short-lived hydroxyl radical $(HO^{\bullet})^{33,36}$ released from the metal $(Fe or Ce)^{35}$ was more efficiently reacting with bromide bonded to the metal because they formed a tight ion-radical pair such as complex I or II (Figure 3e). However, if KBr was used as the source of bromide in the combination with metal salts, the bromide would be surrounded by solvents as a solvated bromide, which disfavored the reaction with the fleeting hydroxyl radical.^{33,36} This hypothesis also explained that organic ligands were ineffective for metal (entry 1-5, Table 2). Taking all of the mechanistic studies and hypothesis together, we could depict the overall mechanism for AchR (Figure 3f). For catalytic cycle 1 (c-1), Fenton chemistry generated an oxygen-based radical (HO[•] and HOO[•]) from H_2O_2 by the Fenton catalyst (Fe^{II} or Ce^{III}), ^{14,32,35} which oxidized bromide to RBS (HOBr).³⁷ For catalytic cycle 2 (c-2), the in situ generated RBS catalyzed the oxidation of furfuryl alcohols (AchR) and released the bromide ion that could be reoxidized by the hydroxyl/hydroperoxyl radical generated from Fenton chemistry. Clearly, Fenton chemistry and bromide redox work in a synergistic way (Figure 3f c-1 and c-2), and FeBr₂ (or CeBr₃) serves as a bifunctional catalyst for AchR (Figure 3f). The detailed hypothesis for the catalytic cycles (c-1 and c-2) of Fenton metal (Fe²⁺ or Ce³⁺) and RBS in our system (M-Br_x-H₂O₂) is provided in the SI, which further demonstrated that M-Br_x serves as a bifunctional catalyst: iron (or cerium) as a catalyst for Fenton chemistry to generate hydroxyl/hydroperoxyl radical oxidants and bromide as a precatalyst for RBS-promoted Achmatowicz rearrangement. Notably, the stepwise mechanisms of AchR using RBS were similar to those that employed NBS or oxone-KBr, which have been well established in the literature.^{1a}

In summary, we discovered that Fenton chemistry can be used for Achmatowicz rearrangement, which represents a new and greenest catalytic protocol (FeBr₂-H₂O₂ and CeBr₃- H_2O_2) for AchR with H_2O as the only byproduct. Four green chemistry metrics, environmental factor (E-factor), atom economy (AE), reaction mass efficiency (RME), and process mass intensity (PMI), were used to evaluate the greenness of our new M-Br_x-H₂O₂ method as compared to our previous oxone-KBr protocol and revealed that the new $M-Br_x-H_2O_2$ was much more efficient and environmentally friendly (sustainable). Our mechanistic study showed that Fenton chemistry operated to generate a fleeting hydroxyl radical, which further oxidized bromide to produce hypobromous acid as the reactive brominating species (RBS) that promote Achmatowicz rearrangement. It is believed that the bromide chemically bonded to the metal without other ligands favors bromide oxidation through a hypothetic ion-radical pair. The discovery of in situ generation of RBS from M-Br_x-H₂O₂ under neutral conditions addresses the long-lasting problem of haloperoxidase mimics that require an acidic additive/medium for bromide oxidation with H₂O₂ and therefore, may create new green opportunities for many other brominium-mediated organic reactions under neutral conditions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acscatal.1c00219.

Detailed screening tables, full experimental procedures, green chemistry metrics analysis, the full mechanistic scheme of catalytic cycles, and characterization data and spectra for all new compounds (PDF)

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Notes

The authors declare no competing financial interest.

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