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Cu-NHC-TEMPO Catalyzed Aerobic Oxidation of Primary Alcohols to Aldehydes

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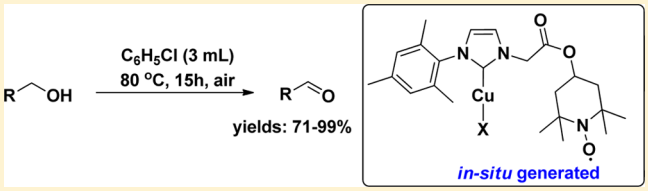
Supporting Information

ABSTRACT: Imidazolium salts bearing TEMPO groups react with commercially available copper powder affording Cu-NHC complexes. The in situ generated Cu-NHC-TEMPO complexes are quite efficient catalysts for aerobic oxidation of primary alcohols into aldehydes. The catalyst is easily available, and various primary alcohols were selectively converted to aldehydes in excellent yields.

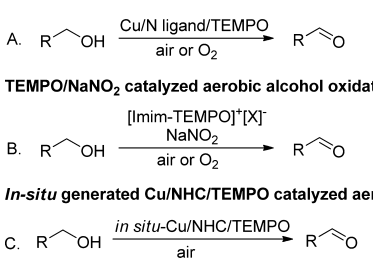


INTRODUCTION

The selective oxidation of alcohols is one of the most fundamental transformations in organic synthesis since their corresponding carbonyl compounds play important roles in total synthesis of natural products and fine chemicals.[1] Classically, chromium and manganese oxides,[2] Swern reagents,[3] and Dess–Martin reagents[4] are often used. However, these stoichiometric oxidants feature serious drawbacks such as employing stoichiometric heavy metal complexes and difficulties in handling hazardous wastes. With ever-increasing environmental concerns, much attention has been devoted to the development of catalytic aerobic alcohol oxidation methodologies.[5] Accordingly, a remarkable number of transition metal-catalyzed aerobic oxidation systems have been well-established including those using copper,[6] palladium,[7] and ruthenium catalysts.[8] Of particular interest are the catalytic systems employing copper salts in combination with 2,2,6,6-tetramethyl-piperidyl-1-oxy (TEMPO),[9] and various N ligands such as 2,2′-bipyridine (Bpy),[9c,h] 1,4-diazabicyclo[2.2.2]octane (DABCO),[9g] and 4,4′-trimethylene-dipyridine (TMDP)[9f] (eq A in Scheme 1). However, additional base is often needed,[9c,d,h] which limits their application in the oxidation of the base-sensitive alcohols. Recently, a transition metal-free system for aerobic oxidations catalyzed by TEMPO/$NaNO_2$ has been developed.[10] Among these results, TEMPO-functionalized imidazolium salts such as $[Imim\text{-}TEMPO]^+X^-$ ($X = Cl^-$, BF_4^-, and $FeCl_4^-$, eq B) have attracted special attention due to their outstanding catalytic and structural properties.[10c−e]

As the potential alternatives to the traditional nitrogen and phosphine ligands, N-heterocyclic carbenes (NHCs) have gained great interest due to their unique properties.[11] The performance of NHCs is easily tuned through introduction of various functional groups at N-positions.[12] We have reported that many transition metal complexes can be easily obtained from the direct reaction of metal powders and imidazolium salts.[13] We speculate that a TEMPO-anchored imidazolium salt combining copper powder would generate a copper-NHC complex bearing TEMPO. Such a complex would be efficient for alcohol oxidation since intramolecular proton abstraction is facile. In continuation of our interest in metal-NHC chemistry of the first transition period,[13a,c,14] herein we present the in situ generated Cu-NHC-TEMPO (eq C) catalyzed aerobic alcohol oxidation. The ligand precursors are easily available, and the present catalyst can be easily prepared from copper powder and showed excellent selectivity of aldehydes in excellent yields under mild conditions in air.

Scheme 1. Strategies toward TEMPO-Involved Aerobic Alcohol Oxidation



RESULTS AND DISCUSSION

The imidazolium salts (**2a**−**2e**) were prepared from *N*-substituted imidazole and 4-(2-haloacetoxy)-TEMPO,[15] and **2f** was prepared following the same procedure by using *N*-mesitylimidazole and cyclohexyl 2-bromoacetate (Scheme 2). Imidazolium salts **2a**−**2e** were isolated as paramagnetic solids. The paramagnetic compounds can be reduced to their corresponding TEMPOH derivatives, which were characterized by ^1H and ^{13}C NMR spectroscopy. The imidazolium salts **2a**−**2f** reacted with commercial copper powder smoothly giving

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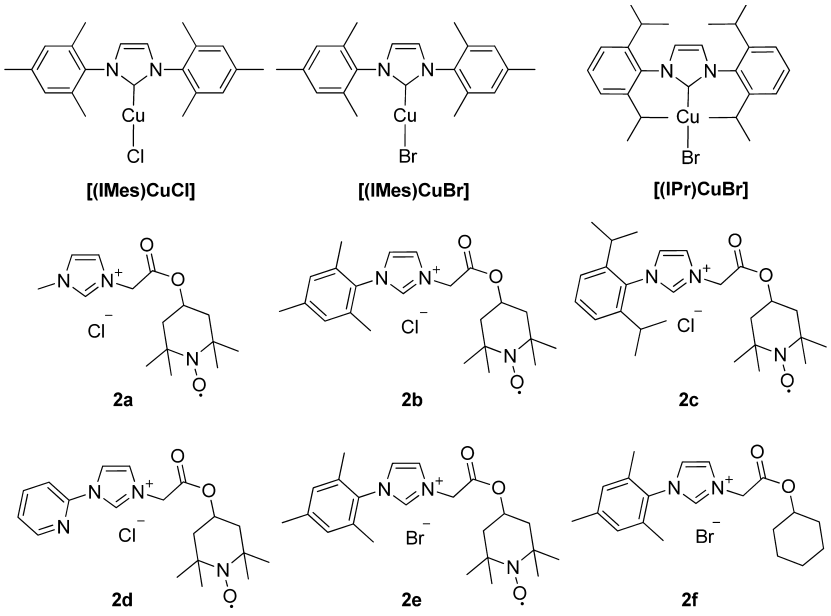
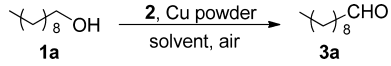
Scheme 2. Cu-NHC Complexes and Ligand Precursors



homogeneous light yellow solutions. We have not been able to obtain single crystals, avoiding full characterization of the resulting copper-NHC complexes. Positive-ion ESI analysis of the solutions from the imidazolium salts with quantitative amount of copper revealed the formation of Cu-NHCs species. EPR spectra of **2b** and its corresponding Cu-NHC-TEMPO complexes were recorded at room temperature, and both pronounced peaks were observed at g = 2.007 characteristic of the nitroxyl radical (see Supporting Information). The in situ generated Cu-NHC complexes were evaluated as catalysts for alcohol oxidation. The initial study was carried out using decan-1-ol (**1a**) as the model substrate to optimize the reaction conditions, and the results were summarized in Table 1. In CH_3CN at 50 °C, all **2a**−**2d** are active, and **2b** is the most efficient one giving decanal in 17% yield (entries 1−4). Blank experiments showed that either copper powder or **2b** itself is totally inefficient (entries 5 and 6). When oxidation of decan-1-ol was attempted using **2b** and CuBr as catalyst, only trace amount of **3a** was obtained (entry 7). The influence of the solvents on the reaction is also apparent (entries 8−12). The oxidation proceeded more efficiently in chlorobenzene than in other solvents, giving a relative higher yield of 36%, and thus was chosen as the solvent for further optimization (entry 9). The yield was significantly increased to 64% when the amount of the catalyst was increased to 10 mol % (entry 13). The reaction was also tested under molecular oxygen, and no significant improvement was observed (entry 14). Base has proved to favor the oxidation reaction of alcohols in most reported Cu/N ligand/TEMPO systems.[9c,d,h] However, bases showed negative effect for the present catalytic system. Addition of KOtBu or Et_3N resulted in obvious decrease of yields to 21 and 19%, respectively (entries 15 and 16). In addition, when **2b** was replaced by **2e**, the yield of decanal was sharply increased to 80%, indicating that the counteranion also plays an important role in oxidation (entry 17). Further increase of the temperature to 80 °C, up to 95% of decanal could be obtained (entry 18). Combination of **2f** and copper powder showed no activity. For comparison, the catalytic activities of [(IMes)CuCl], [(IMes)CuBr], and [(IPr)CuBr] complexes were also examined. [(IMes)CuBr] and [(IPr)-CuBr] themselves are totally inactive. Unexpectedly, their combinations with TEMPO only showed negligible activity with trace amount of decanal (**3a**) detected (entries 21 and 22). The copper-catalyzed alcohol oxidation often involves the use of *N*-ligands, and the catalytic activity of Cu-NHC complexes

Table 1. Optimization of Reaction Conditions[a]



1a 3a

entry	cat (mol %)	solvent	temp (°C)	additive (mol %)	yield (%)[b]
1	**2a** + Cu (5)	CH_3CN	50		12
2	**2b** + Cu (5)	CH_3CN	50		17
3	**2c** + Cu (5)	CH_3CN	50		9
4	**2d** + Cu (5)	CH_3CN	50		14
5	**2b** (5)	CH_3CN	50		NR
6	Cu (5)	CH_3CN	50		NR
7	**2b** + CuBr (5)	CH_3CN	50		trace
8	**2b** + Cu (5)	DMSO	50		27
9	**2b** + Cu (5)	C_6H_5Cl	50		36
10	**2b** + Cu (5)	Toluene	50		24
11	**2b** + Cu (5)	THF	50		trace
12	**2b** + Cu (5)	DMF	50		trace
13	**2b** + Cu (10)	C_6H_5Cl	50		64
14	**2b** + Cu (10)	C_6H_5Cl	50		67[c]
15	**2b** + Cu (10)	C_6H_5Cl	50	KOtBu (10)	21
16	**2b** + Cu (10)	C_6H_5Cl	50	Et_3N (10)	19
17	**2e** + Cu (10)	C_6H_5Cl	50		80
18	**2e** + **Cu (10)**	**C_6H_5Cl**	**80**		**95**
19	**2f** + Cu (10)	C_6H_5Cl	80		NR
20	[(IMes)CuCl] (10)	C_6H_5Cl	80		NR
21	[(IMes)CuBr] (5)	CH_3CN	50	TEMPO (5)	trace
22	[(IPr)CuBr] (5)	CH_3CN	50	TEMPO (5)	trace

[a]Reaction conditions: Imidazolium salt and copper powder were stirred at 70 °C for 5 h before addition of alcohol (1.0 mmol), and the stirring was continued for 15 h in air. [b]GC yield. [c]O_2.

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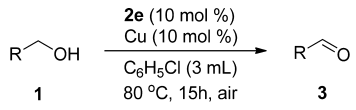
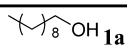
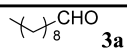
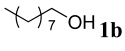
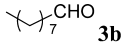
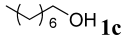
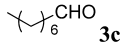
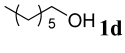
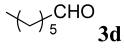
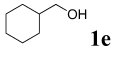
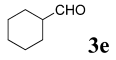
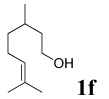
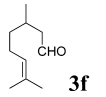
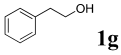
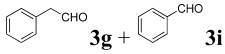
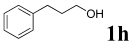
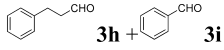
was not yet explored. The results showed that simple combinations of commonly used Cu-NHC complexes such as [(IPr)CuX] or [(IMes)CuX] and TEMPO do not show activities for alphatic alcohol **1a**. However, the catalytic activity of Cu-NHCs bearing a TEMPO was greatly improved. The mechanism is still unclear, and it was tentatively proposed that Cu-NHC complex anchored TEMPO is efficient for alcohol oxidation since intramolecular proton abstraction is facile.

To probe the efficiency of the in situ Cu-NHC-TEMPO catalytic system, the oxidation of other aliphatic alcohols were examined under the optimized conditions as summarized in Table 2. Studies commenced with the oxidation of straight-

Table 2. Aerobic Oxidation of Aliphatic Primary Alcohols[a]



entry	alcohols	product	yield %[b]
1	 **1a**	 **3a**	95 (76)
2	 **1b**	 **3b**	91
3	 **1c**	 **3c**	90
4	 **1d**	 **3d**	88
5	 **1e**	 **3e**	86
6	 **1f**	 **3f**	99 (85)
7	 **1g**	 **3g** + **3i**	trace + 34
8	 **1h**	 **3h** + **3i**	13 + 60

[a]Reaction conditions: **2e** (0.1 mmol, 10 mol %) and copper powder (0.1 mmol, 10 mol %) in chlorobenzene (3 mL) were stirred at 70 °C for 5 h before addition of alcohol (1.0 mmol), and the stirring was continued at 80 °C for 15 h. [b]GC yield.

chain C_7−C_{10} alcohols, and all these primary alcohols were selectively oxidized to aldehydes in GC yields of 88−95% (entries 1−4). Cyclohexylmethanol (**1e**) could also be converted into its corresponding product in a slightly lower yield of 86% (entry 5). An almost quantitative transformation was obtained when 3,7-dimethyloct-6-en-1-ol (**1f**) was applied, and no over oxidation of the alkene was observed (entry 6). However, a C−C cleavage was observed for the oxidation of 2-phenylethanol and 3-phenylpropan-1-ol under the same conditions giving benzaldehyde as the major product in moderate yields (entries 7 and 8).

The aerobic oxidation of various benzylic, allylic, propargylic, and heterocyclic-substituted alcohols was also investigated (Table 3). As have been reported, benzylic alcohols usually show higher reactivities than aliphatic alcohols.[9] Hence, phenylmethanol (**1i**) was first tested with a catalyst loading of 1 mol %, and the reaction afforded benzaldehyde in 75% yield within 15 h at 80 °C (Table 3, entry 1). When the amount of the catalyst was doubled, the oxidation of phenylmethanol was completed within 15 h in 96% yield (entry 1). At the catalyst loading of 2 mol %, both benzylic alcohols with either electron-donating or electron-withdrawing substituents can be oxidized into their corresponding aldehydes in excellent yields (entries 2−10). However, the oxidation of (4-nitrophenyl)-methanol (**1q**) and (2-nitrophenyl)methanol (**1r**) has to elongate to 20 h to reach completion (entries 9 and 10). Anthracen-9-ylmethanol (**1t**) is much more inert than naphthalen-1-ylmethanol (**1s**), and anthracene-10-carbaldehyde (**3t**) was obtained in only 49% yield at a catalyst loading of 2 mol %, probably because of the steric effect (entries 11 and 12). When the catalyst loading was increased to 5%, **3t** could be isolated in 94% yield (entry 12). Under the same conditions, 3-phenylprop-2-yn-1-ol (**1u**) and 3-phenylprop-2-en-1-ol (**1v**) could be also almost quantitatively transformed into their corresponding aldehydes, and no over oxidation products were observed (entries 13 and 14). The heteroaryl alcohols such as furan-2-ylmethanol (**1w**) and thiophen-2-ylmethanol (**1x**) were smoothly transformed into their aldehyde products in 71 and 73% yields, respectively (entries 15 and 16). However, no oxidation was observed with pyridin-2-ylmethanol (**1y**) (entry 17).

■ CONCLUSION

In summary, in situ generated Cu-NHC-TEMPO catalyzed aerobic oxidation of primary alcohols into aldehydes is presented. The catalytic system was applicable to various primary alcohols, and their aldehydes were selectively obtained in excellent yields. At present, the structural changes of the catalyst in the catalytic cycle were unclear. The isolation of the catalyst after completion of oxidation had difficulty proceeding because of its low catalyst loading and good solubility in chlorobenzene. To fully understand the catalytic performance, further work will be done.

■ EXPERIMENTAL SECTION

All the chemicals were obtained from commercial suppliers and used without further purification. [(IMes)CuCl],[16] [(IMes)CuBr],[16] [(IPr)-CuBr],[16] 2-haloacetoxy-substituted complexes,[15a,17] and carbene precursor **2a**[15a] were prepared according to the known procedure. The paramagnetic **2b**−**2e** were characterized by elemental analyses and further identified by ^{1}H and ^{13}C spectroscopy after reduction to their corresponding TEMPOH derivatives using phenlyhydrazine as the reductant.[15a]

Synthesis of Imidazolium Salt 2b. A solution of *N*-mesitylimidazole (1.86 g, 10 mmol) and 4-(2-chloroacetoxy)-TEMPO (2.98 g, 12 mmol) in 30 mL of CH_3CN was refluxed for 12 h. The solution was then concentrated to ca. 5 mL. Addition of ethyl acetate (20 mL) to the resulting solution afforded an orange yellow precipitate, which was collected and washed with ethyl acetate (10 mL × 3). Yield: 4.05 g, 93%. Anal. Calcd for $C_{23}H_{33}ClN_3O_3$: C, 63.51; H, 7.65; N, 9.66. Found: C, 63.18; H, 7.87; N, 9.62. The hydroxyl form: ^{1}H NMR (400 MHz, D_2O) δ 7.73 (s, 1H), 7.59 (s, 1H), 7.12 (s, 2H), 5.27−5.25 (m, 3H), 2.30 (s, 3H), 2.15−2.12 (m, 2H), 2.01 (s, 6H), 1.72 (t, J = 11.2 Hz, 2H), 1.27 (s, 6H), 1.25 (s, 6H); ^{13}C NMR (100 MHz, D_2O) δ 166.8, 141.4, 137.9, 134.4, 130.4, 129.0, 124.0, 123.8, 68.6, 65.9, 63.0, 50.2, 41.2, 28.6, 20.0, 16.1.

Synthesis of Imidazolium Salt 2c. Complex **2c** was obtained as a light yellow solid following the same procedure as for **2b** by using *N*-2,6-diisopropylphenylimidazole (2.28 g, 10 mmol) and 4-(2-chloroacetoxy)-TEMPO (2.98 g, 12 mmol). Yield: 4.15 g, 87%. Anal. Calcd for $C_{26}H_{39}ClN_3O_3$: C, 65.46; H, 8.24; N, 8.81. Found: C, 65.73; H, 8.19; N, 8.77. The hydroxyl form: ^{1}H NMR (400 MHz, D_2O) δ 7.75 (s, 1H), 7.72 (s, 1H), 7.59 (t, J = 7.8 Hz, 1H), 7.42 (d, J =

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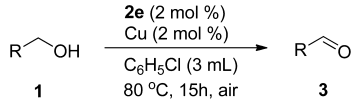
Table 3. Aerobic Oxidation of Substituted Benzylic and Other Active Alcohols[a]



entry	alcohol	product	yield %
1	1i	3i	75[b,c] 96[b]
2	1j	3j	84
3	1k	3k	94
4	1l	3l	95
5	1m	3m	81
6	1n	3n	85
7	1o	3o	92
8	1p	3p	94
9	1q	3q	98[d]
10	1r	3r	97[d]
11	1s	3s	99
12	1t	3t	49 94[e]
13	1u	3u	24 94[e]
14	1v	3v	95[e]
15	1w	3w	71
16	1x	3x	73
17	1y	3y	-

[a]Reaction conditions: **2e** (0.02 mmol, 2 mol %) and copper powder (0.02 mmol, 2 mol %) in chlorobenzene (3 mL) were stirred at 70 °C for 5 h before addition of alcohol (1.0 mmol), and the stirring was continued at 80 °C for 15 h. [b]GC yield. [c]**2e** 0.01 mmol (1 mol %) and copper powder 0.01 mmol (1 mol %) were used. [d]20 h. [e]**2e** 0.05 mmol (5 mol %) and copper powder 0.05 mmol (5 mol %) were used.

8.0 Hz, 2H), 5.25−5.22 (m, 3H), 2.35−2.28 (m, 2H), 2.06−2.03 (m, 2H), 1.62 (t, J = 12.0 Hz, 2H), 1.19 (s, 6H), 1.17 (s, 6H), 1.11 (s, 12H); ^{13}C NMR (100 MHz, D_2O) δ 166.8, 145.4, 131.7, 129.8, 125.0, 124.3, 124.2, 124.0, 69.6, 60.6, 50.2, 41.9, 29.5, 28.1, 23.1, 22.9.

Synthesis of Imidazolium Salt 2d. Complex **2d** was obtained as a yellow solid following the same procedure as for **2b** by using 2-(imidazolyl)pyridine (1.45 g, 10 mmol) and 4-(2-chloroacetoxy)-TEMPO (2.98 g, 12 mmol). Yield: 2.98 g, 76%. Anal. Calcd for $C_{19}H_{26}ClN_4O_3$: C, 57.94; H, 6.65; N, 14.22. Found: C, 57.67; H, 6.82; N, 14.13. The hydroxyl form: ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.06 (s, 1H), 8.66 (s, 1H), 8.57 (s, 1H), 8.23 (s, 1H), 8.06−8.00 (m, 2H), 7.67 (s,1H), 7.42 (s, 1H), 5.32 (s, 2H), 5.13−5.08 (m, 1H), 1.98−1.92 (m, 2H), 1.56−1.51 (m, 2H), 1.10 (s, 6H), 1.09 (s, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 166.1, 149.4, 146.2, 140.8, 136.2, 125.5, 125.0, 119.0, 114.3, 69.1, 58.2, 50.2, 43.3, 32.0, 20.4.

Synthesis of Imidazolium Salt 2e. Complex **2e** was obtained as a yellow solid following the same procedure as for **2b** by using *N*-mesitylimidazole (1.86 g, 10 mmol) and 4-(2-bromoacetoxy)-TEMPO (3.52 g, 12 mmol). Yield: 4.25 g, 89%. Anal. Calcd for $C_{23}H_{33}BrN_3O_3$: C, 57.62; H, 6.94; N, 8.76. Found: C, 57.57; H, 7.02; N, 8.56. The hydroxyl form: ^{1}H NMR (400 MHz, D_2O) δ 7.74 (s, 1H), 7.57 (s, 1H), 7.11 (s, 2H), 5.27−5.25 (m, 3H), 2.29 (s, 3H), 2.17−2.14 (m, 2H), 2.01 (s, 6H), 1.74 (t, J = 11.6 Hz, 2H), 1.27 (s, 3H), 1.26 (s, 3H); ^{13}C NMR (100 MHz, D_2O) δ 166.8, 141.4, 137.6, 134.4, 130.4, 129.1, 124.0, 123.8, 68.7, 65.9, 63.0, 50.2, 41.3, 28.6, 20.0, 16.2.

Synthesis of Imidazolium Salt 2f. A solution of *N*-mesitylimidazole (1.86 g, 10 mmol) and cyclohexyl 2-bromoacetate (2.65 g, 12 mmol) in 30 mL of toluene was refluxed for 12 h. The resulting white solid was filtered and washed with Et_2O (10 mL × 3). Yield: 3.50 g, 86%. Anal. Calcd for $C_{20}H_{27}BrN_2O_2$: C, 58.97; H, 6.68; N, 6.88. Found: C, 58.74; H, 6.55; N, 7.02. Spectral data: ^{1}H NMR (400 MHz, DMSO-d_6) δ 9.58 (s, 1H), 8.13 (s, 1H), 8.00 (s, 1H), 7.16 (s, 2H), 5.42 (s, 2H), 4.85−4.81 (m, 1H), 2.33 (s, 3H), 2.03 (s, 6H), 1.81 (br, 2H), 1.63 (br, 2H), 1.46−1.24 (m, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.9, 140.3, 138.9, 134.2, 131.1, 129.3, 124.5, 123.4, 74.3, 50.1, 30.8, 24.7, 22.8, 20.6, 16.8.

General Procedure for the Synthesis of Products 3. For aliphatic primary alcohols: In a glass tube, a mixture of **2e** (48 mg, 0.1 mmol) and copper powder (6.5 mg, 0.1 mmol) in 3.0 mL of chlorobenzene was stirred 70 °C for 5 h under air. Then alcohol (1.0 mmol) was added, and the stirring was continued at 80 °C for 15 h. After completion of the oxidation, the resulting solution was cooled to room temperature. The reaction mixture was concentrated under reduced pressure. The residue was purified by flash column chromatography on silica gel (ethyl acetate/petroleum ether) to afford the aldehyde products. For substituted benzylic and other active alcohols: 2 mol % of **2e** and copper powder were used following the same procedure described above unless otherwise stated.

*Decanal (**3a**).*[9b] Colorless oil; yield: 119 mg, 76%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.73 (s, 1H), 2.39 (t, J = 7.4 Hz, 2H), 1.61−1.57 (m, 2H), 1.26−1.23 (m, 12H), 0.84 (t, J = 6.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.0, 44.0, 31.9, 29.5, 29.4, 29.3, 29.2, 22.7, 22.2, 14.2.

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*3,7-Dimethyloct-6-enal (**3f**).*[9b]* Colorless oil; yield: 131 mg, 85%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.72 (m, 1H), 5.06 (t, J = 6.8 Hz, 1H), 2.41−2.35 (m, 1H), 2.23−2.17 (m, 1H), 2.07−1.94 (m, 3H), 1.65 (s, 3H), 1.57 (s, 3H), 1.35−1.23 (m, 2H), 0.94 (d, J = 6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.1, 131.8, 124.1, 51.1, 37.0, 27.8, 25.8, 25.5, 19.9, 17.7.

*4-Methylbenzaldehyde (**3j**).*[9e]* Colorless oil; yield: 101 mg, 84%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.94 (s, 1H), 7.76 (d, J = 7.6 Hz, 2H), 7.31 (d, J = 8.4 Hz, 2H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.2, 145.7, 134.2, 129.9, 129.8, 22.0.

*4-Methoxybenzaldehyde (**3k**).*[9e]* Colorless oil; yield: 128 mg, 94%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.85 (s, 1H), 7.81 (d, J = 8.8 Hz, 2H), 6.98 (d, J = 8.4 Hz, 2H), 3.86 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.0, 164.6, 132.1, 129.9, 114.3, 55.6.

*4-(Dimethylamino)benzaldehyde (**3l**).*[6d]* Light yellow solid; yield: 142 mg, 95%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.72 (s, 1H), 7.72 (d, J = 8.8 Hz, 2H), 6.68 (d, J = 8.8 Hz, 2H), 3.06 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.4, 154.4, 132.0, 125.1, 111.1, 40.1.

*3,4-Dimethoxybenzaldehyde (**3m**).*[9e]* White solid; yield: 134 mg, 81%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.79 (s, 1H), 7.40 (d, J = 8.0 Hz, 1H), 7.34 (s, 1H), 6.92 (d, J = 8.4 Hz, 1H), 3.91 (s, 3H), 3.88 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.9, 154.4, 149.5, 130.1, 126.9, 110.3, 108.8, 56.2, 55.9.

*4-Chlorobenzaldehyde (**3n**).*[18]* White solid; yield: 119 mg, 85%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.97 (s, 1H), 7.81 (d, J = 8.4 Hz, 2H), 7.50 (d, J = 8.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.1, 141.0, 134.8, 131.0, 129.6.

*4-Bromobenzaldehyde (**3o**).*[9e]* White solid; yield: 170 mg, 92%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.95 (s, 1H), 7.75−7.72 (m, 2H), 7.68−7.66 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.2, 135.1, 132.5, 131.1, 129.9.

*2-Bromobenzaldehyde (**3p**).*[9b]* Colorless oil; yield: 174 mg, 94%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.35 (s, 1H), 7.91−7.89 (m, 1H), 7.64 (d, J = 7.2 Hz, 1H), 7.47−7.40 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.1, 135.5, 134.0, 133.5, 130.0, 128.0, 127.3.

*4-Nitrobenzaldehyde (**3q**).*[9e]* Yellow solid; yield: 148 mg, 98%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.15 (s, 1H), 8.38 (d, J = 8.8 Hz, 2H), 8.07 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.4, 151.3, 140.2, 130.6, 124.4.

*2-Nitrobenzaldehyde (**3r**).*[10e]* Yellow solid; yield: 146 mg, 97%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.36 (s, 1H), 8.09 (d, J = 8.0 Hz, 1H), 7.92−7.90 (m, 1H), 7.81−7.74 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.3, 149.5, 134.2, 133.8, 131.3, 129.7, 124.6.

*1-Naphthaldehyde (**3s**).*[6d]* Light yellow oil; yield: 154 mg, 99%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.34 (s, 1H), 9.25 (d, J = 8.4 Hz, 1H), 8.03 (d, J = 8.4 Hz, 1H), 7.91−7.86 (m, 2H), 7.67 (t, J = 7.6 Hz, 1H), 7.58−7.54 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.6, 136.8, 135.3, 133.6, 131.2, 130.4, 129.0, 128.4, 126.9, 124.8.

*Anthracene-9-carbaldehyde (**3t**).*[18]* Yellow solid; yield: 194 mg, 94%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 11.52 (s, 1H), 8.98 (d, J = 9.2 Hz, 2H), 8.69 (s, 1H), 8.06 (d, J = 8.4 Hz, 2H), 7.69 (t, J = 7.6 Hz, 2H), 7.55 (t, J = 7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.2, 135.5, 132.3, 131.2, 129.4, 129.3, 125.8, 124.7, 123.6.

*3-Phenylpropiolaldehyde (**3u**).*[9h]* Light yellow oil; yield: 122 mg, 94%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.40 (s, 1H), 7.59 (d, J = 7.2 Hz, 2H), 7.48 (t, J = 7.4 Hz, 1H), 7.39 (t, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.9,133.3, 131.3, 128.7, 119.3, 95.1, 88.4.

*Cinnamaldehyde (**3v**).*[9e]* Colorless oil; yield: 125 mg, 95%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.68 (d, J = 7.6 Hz, 1H), 7.55−7.53 (m, 2H), 7.47−7.41 (m, 4H), 6.72−6.66 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.8, 152.9, 133.9, 131.3, 129.1, 128.7, 128.5.

*Furan-2-carbaldehyde (**3w**).*[9h]* Light yellow oil; yield: 68 mg, 71%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.55 (s, 1H), 7.61 (s, 1H), 7.17 (d, J = 3.6 Hz, 1H), 6.51 (d, J = 2.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.7, 152.9, 148.0, 121.1, 112.5.

*Thiophene-2-carbaldehyde (**3x**).*[9h]* Light yellow oil; yield: 82 mg, 73%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.90 (s, 1H), 7.77−7.72 (m, 2H), 7.18 (t, J = 4.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 183.1, 143.9, 136.5, 135.2, 128.4.

■ ASSOCIATED CONTENT

Supporting Information

Copies of ^{1}H and ^{13}C NMR spectra for **2b**−**2f** and **3a**−**3x**, ESI analysis of the in situ generated Cu-NHC species, and EPR spectra of **2b** and its corresponding Cu-NHC-TEMPO species. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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