

Simple copper/TEMPO catalyzed aerobic dehydrogenation of benzylic amines and anilines

Zhenzhong Hu and Francesca M. Kerton,*

Department of Chemistry, Memorial University of Newfoundland, St. John's, NL,
A1B 3X7, Canada. E-mail: fkerton@mun.ca

Contents

General experimental information (Page 1)

General procedure for the synthesis of imines (Page 1)

General procedure for the synthesis of diazenes (Page 3)

References (Page 4)

Screening with different catalyst loading for oxidation of dibenzylamine (Page 5)

Kinetic study of the oxidation of dibenzylamine (Page 4)

¹H NMR and ¹³C NMR spectra of selected imine and azo compounds (Page 7-26)

General experimental information

Amines and other chemicals were purchased from Aldrich and Alfa and were used without further purification. The ¹H NMR spectra of the products were acquired on a Bruker AVANCE 500 MHz spectrometer. The ¹³C NMR spectra were obtained on a Bruker AVANCE III 300 MHz spectrometer equipped with a BBFO probe. Chemical shifts were reported in ppm using the tetramethylsilane ($\delta = 0$ ppm) in CDCl₃ or Acetone-d₆ as an internal standard. Conversions were determined by GC-MS (Gas Chromatography Mass Spectrometry) analyses using an Agilent Technologies 7890 GC system coupled to an Agilent Technologies 5975C mass selective detector (MSD). Dodecane was used as an internal standard. The GC system was equipped with electronic pressure control, split/splitless and on-column injectors, and an HP5-MS column. EI-MS spectra were obtained on this Agilent instrument. HRMS were obtained using a Waters GC system and GCT Premier Micromass system. IR spectra were acquired with a Bruker-Alfa spectrometer. Elemental analyses were performed by either Canadian Microanalytical Service Ltd., Delta, BC, or Guelph Chemical Laboratories Ltd., Guelph, ON, Canada.

General procedure for the synthesis of imines

The oxidation reactions were carried out under air in a 25 ml three-necked round-bottomed flask equipped with a magnetic stirrer. Typically, 4.0 mmol benzylamine was dissolved in 6 ml acetonitrile and 3 ml water. 0.10 mmol (22.3 mg) of CuBr₂ and 0.10 mmol (15.6 mg)

TEMPO were then added leading to a blue solution. The reaction mixture was stirred vigorously at room temperature for 12 h. After reaction completion, the mixture was extracted with diethyl ether. Then the organic layer was washed with water and brine. The organic phase was dried with anhydrous magnesium sulfate and filtered through a short silica column. After concentrating under vacuum, the product was obtained without further purification.

N-(benzylidene)benzylamine (entry 1, Table 2). Data in agreement with literature.¹ ¹H NMR (CDCl₃, 500 MHz): δ = 8.33 (s, 1H), 7.77-7.74 (m, 2H), 7.39-7.35 (m, 3H), 7.34-7.26 (m, 4H), 7.25-7.21 (m, 1H), 4.78 (s, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ = 161.84, 139.16, 136.00, 130.65, 128.50, 128.40, 128.18, 127.88, 126.88, 64.93 ppm. MS (EI): m/z (%) 195 [M]⁺ (25), 194 (26), 117 (14), 91 (100), 65 (16). Anal. Calc. for C₁₄H₁₃N: C, 86.12; H, 6.71; N, 7.17. Found: C, 85.84; H, 6.77; N, 6.97.

2-Methoxy-*N*-(2-methoxybenzylidene)benzylamine (entry 2, Table 2). ¹H NMR (CDCl₃, 500 MHz): δ = 8.84 (s, 1H), 8.03 (d, *J* = 7.3 Hz, 1H), 7.40-7.28 (m, 2H), 7.22 (t, *J* = 7.3 Hz, 1H), 7.03-6.81 (m, 4H), 4.82 (s, 2H), 3.84 (s, 3H), 3.82 (s, 3H); ¹³C NMR (CDCl₃, 75 MHz): δ = 155.73, 155.24, 154.01, 128.82, 126.09, 125.12, 124.94, 124.46, 121.85, 117.77, 117.53, 108.04, 107.20, 56.65, 52.75, 52.51 ppm. MS (EI): m/z (%) 255 [M]⁺ (12), 254 (10), 148 (8), 134 (93), 121 (89), 91 (100), 77 (19), 65 (18). Anal. Calc. for C₁₆H₁₇NO₂: C, 75.27; H, 6.71; N, 5.49. Found: C, 74.98; H, 6.69; N, 5.41.

3-Methoxy-*N*-(3-methoxybenzylidene)benzylamine (entry 3, Table 2). ¹H NMR (CDCl₃, 500 MHz): δ = 8.33 (s, 1H), 7.38 (s, 1H), 7.34-7.22 (m, 3H), 6.98-6.90 (m, 3H), 6.80 (d, *J* = 8.3 Hz, 1H), 4.78 (s, 2H), 3.82 (s, 3H), 3.79 (s, 3H); ¹³C NMR (CDCl₃, 75 MHz): δ = 160.36, 158.24, 158.11, 139.17, 135.92, 127.94, 127.86, 120.01, 118.68, 115.93, 111.99, 110.80, 110.02, 63.25, 53.81, 53.64 ppm. MS (EI): m/z (%) 255 [M]⁺ (52), 254(40), 122 (100), 121 (80), 91 (32), 77 (23), 65 (10). Anal. Calc. for C₁₆H₁₇NO₂: C, 75.27; H, 6.71; N, 5.49. Found: C, 74.98; H, 6.55; N, 5.27.

4-Methoxy-*N*-(4-methoxybenzylidene)benzylamine (entry 4, Table 2). Data in agreement with literature.² ¹H NMR (Acetone-d₆, 500 MHz): δ = 8.36 (s, 1H), 7.74 (d, *J* = 8.4 Hz, 2H), 7.25 (d, *J* = 8.3 Hz, 2H), 6.97 (d, *J* = 8.4 Hz, 2H), 6.88 (d, *J* = 8.3 Hz, 2H), 3.83 (s, 2H), 3.76 (s, 2H); ¹³C NMR (Acetone-d₆, 75 MHz): δ = 162.77, 161.27, 159.72, 133.21, 130.67, 130.07, 114.96, 114.71, 65.11, 56.05, 55.78 ppm. MS (EI): m/z (%) 255 [M]⁺ (13), 122 (11), 121 (100), 77 (10). Anal. Calc. for C₁₆H₁₇NO₂: C, 75.27; H, 6.71; N, 5.49. Found: C, 75.23; H, 6.68; N, 5.43.

4-Methyl-*N*-(4-methylbenzylidene)benzylamine (entry 5, Table 2). Data in agreement with literature.² ¹H NMR (CDCl₃, 500 MHz): δ = 8.34 (s, 1H), 7.66 (d, *J* = 8.0 Hz, 2H), 7.25-7.13 (m, 6H), 4.76 (s, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ = 161.68, 140.96, 136.51, 136.36, 133.63, 129.30, 129.15, 128.24, 127.95, 64.81, 21.51, 21.10 ppm. MS (EI): m/z (%) 223 [M]⁺ (38), 222 (20), 131 (10), 106 (24), 105 (100), 91 (9), 77 (12). Anal. Calc. for C₁₆H₁₇N: C, 86.05; H, 7.67; N, 6.27. Found: C, 86.22; H, 7.58; N, 6.46.

2-Chloro-*N*-(2-chlorobenzylidene)benzylamine (entry 7, Table 2). Data in agreement with literature.¹H NMR (CDCl₃, 500 MHz): δ = 8.86 (s, 1H), 8.11(d, J = 7.5 Hz, 1H), 7.43-7.20 (m, 7H), 4.94 (s, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ = 158.84, 135.94, 134.42, 132.53, 132.22, 130.89, 128.97, 128.80, 128.48, 127.59, 127.46, 126.17, 126.06, 61.32 ppm. MS (EI): m/z (%) 263 [M]⁺ (20), 264 (14), 265 (14), 262 (16), 228 (9), 151 (10), 125 (100), 126 (12), 127 (35), 89 (28). Anal. Calc. for C₁₄H₁₁Cl₂N: C, 63.66; H, 4.20; N, 5.30. Found: C, 63.78; H, 4.27; N, 5.37.

4-Chloro-*N*-(4-chlorobenzylidene)benzylamine (entry 8, Table 2). Data in agreement with literature.¹H NMR (CDCl₃, 500 MHz): δ = 8.33 (s, 1H), 7.70 (d, J = 8.5 Hz, 2H), 7.38 (d, J = 8.5 Hz, 2H), 7.32-7.25 (m, 4H), 4.76 (s, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ = 160.81, 137.60, 136.86, 134.44, 132.81, 129.44, 129.24, 128.91, 128.62, 64.15 ppm. MS (EI): m/z (%) 263 [M]⁺ (16), 264 (12), 265 (14), 262 (13), 151 (14), 125 (100), 126 (12), 127 (30), 89 (20). Anal. Calc. for C₁₄H₁₁Cl₂N: C, 63.66; H, 4.20; N, 5.30. Found: C, 63.77; H, 4.19; N, 5.27.

3,4-Dihydroisoquinoline (entry 11, Table 2). Data in agreement with literature.³ ¹H NMR (CDCl₃, 500 MHz): δ = 8.33 (s, 1H), 7.35 (td, J = 7.2, 1.1 Hz, 1H), 7.31-7.26 (m, 2H), 7.15 (d, J = 7.3 Hz, 1H), 3.79-3.76 (m, 2H), 2.75 (t, J = 7.5 Hz, 2H); ¹³C NMR (CDCl₃, 75 MHz): δ = 160.33, 136.30, 131.05, 128.49, 127.43, 127.20, 127.09, 47.41, 25.04 ppm. MS (EI): m/z (%) 131 [M]⁺ (92), 130 (100), 103 (30), 104 (26), 77 (C₆H₅, 22). Anal. Calc. for C₉H₉N: C, 82.41; H, 6.92; N, 10.68. Found: C, 82.31; H, 6.80; N, 10.66.

General procedure for the synthesis of diazenes

The oxidative homo-coupling of anilines to diphenyldiazenes were carried out under air in a 25 ml reaction tube using a Radleys Carousel ReactorTM equipped with a magnetic stirrer. Typically, 4-methoxybenzenamine (492 mg, 4 mmol) was dissolved in 9 ml acetonitrile; CuBr (21 mg, 0.15 mmol) and TEMPO (23.4 mg, 0.15 mmol) were then added. The reaction mixture was stirred vigorously at 60 °C for 18 h. After completing, the reaction mixture was extracted with diethyl ether. Then the organic layer was washed with water and brine. The organic phase was dried with anhydrous magnesium sulfate and filtered through a short silica column. After concentrating under vacuum, the product was obtained without further purification.

(*E*)-1,2-Diphenyldiazene (entry 1, Table 4). Data in agreement with literature.⁴ ¹H NMR (CDCl₃, 500 MHz): δ = 7.97-7.87 (m, 4H), 7.55-7.44 (m, 6H); ¹³C NMR (CDCl₃, 75 MHz): δ = 152.65, 130.97, 129.08, 122.83 ppm; IR (neat): ν = 3061, 1581, 1482, 1452, 1298, 1220, 925, 771, 685 cm⁻¹. MS (EI): m/z (%) 182 [M]⁺ (36), 105 (21), 77 (100). HRMS (TOF MS EI+) m/z calcd for C₁₂H₁₀N₂ 182.0845, found 182.0844. Anal. Calc. for C₁₂H₁₀N₂: C, 79.10; H, 5.53; N, 15.37. Found: C, 78.80; H, 5.44; N, 15.12

(*E*)-1,2-Di-*o*-tolylidiazene (entry 2, Table 4). Data in agreement with literature.⁴ ¹H NMR (CDCl₃, 500 MHz): δ = 7.62 (d, *J* = 8.0 Hz, 2H), 7.38-7.29 (m, 4H), 7.28-7.23 (m, 2H), 2.74 (s, 6H); ¹³C NMR (CDCl₃, 75 MHz): δ = 151.10, 137.97, 131.27, 130.69, 126.37, 115.85, 17.63 ppm; IR (neat): ν = 2924, 1596, 1477, 1192, 1150, 1039, 768, 715 cm⁻¹. MS (EI): *m/z* (%) 210 [M]⁺ (28), 119 (10), 91 (100), 65 (30). HRMS (TOF MS EI+) *m/z* calcd for C₁₄H₁₄N₂ 210.1157, found 210.1156. Anal. Calc. for C₁₄H₁₄N₂: C, 79.97; H, 6.71; N, 13.32. Found: C, 80.13; H, 6.59; N, 12.97

(*E*)-1,2-Bis(3,5-dimethylphenyl)diazene (entry 3, Table 4). Data in agreement with literature.⁴ ¹H NMR (CDCl₃, 500 MHz): δ = 7.52 (s, 4H), 7.11 (s, 2H), 2.44 (s, 12H); ¹³C NMR (CDCl₃, 75 MHz): δ = 152.90, 138.74, 132.51, 120.54, 21.26 ppm; IR (neat): ν = 2914, 1608, 1442, 1292, 1038, 903, 853 cm⁻¹. MS (EI): *m/z* (%) 238 [M]⁺ (40), 105 (100), 78 (18), 77 (25). HRMS (TOF MS EI+) *m/z* calcd for C₁₆H₁₈N₂ 238.1470, found 238.1469. Anal. Calc. for C₁₆H₁₈N₂: C, 80.63; H, 7.61; N, 11.75. Found: C, 80.80; H, 7.63; N, 11.91

(*E*)-1,2-Bis(4-methoxyphenyl)diazene (entry 4, Table 4). Data in agreement with literature.⁴ ¹H NMR (CDCl₃, 500 MHz): δ = 7.88 (d, *J* = 9.0 Hz, 2H), 7.70 (d, *J* = 9.0 Hz, 4H), 3.89 (s, 6H); ¹³C NMR (CDCl₃, 75 MHz): δ = 161.56, 147.07, 124.34, 114.16, 55.57 ppm; IR (neat): ν = 3413, 1592, 1579, 1496, 1249, 841 cm⁻¹. MS (EI): *m/z* (%) 242 [M]⁺ (75), 243 (10), 135 (31), 107 (100), 92 (32), 77 (50), 64 (13). HRMS (TOF MS EI+) *m/z* calcd for C₁₄H₁₄N₂O₂ 242.1059, found 242.1055. Anal. Calc. for C₁₄H₁₄N₂O₂: C, 69.41; H, 5.82; N, 11.56. Found: C, 69.51; H, 5.55; N, 11.66

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Screening with different catalyst loading for oxidation of dibenzylamine

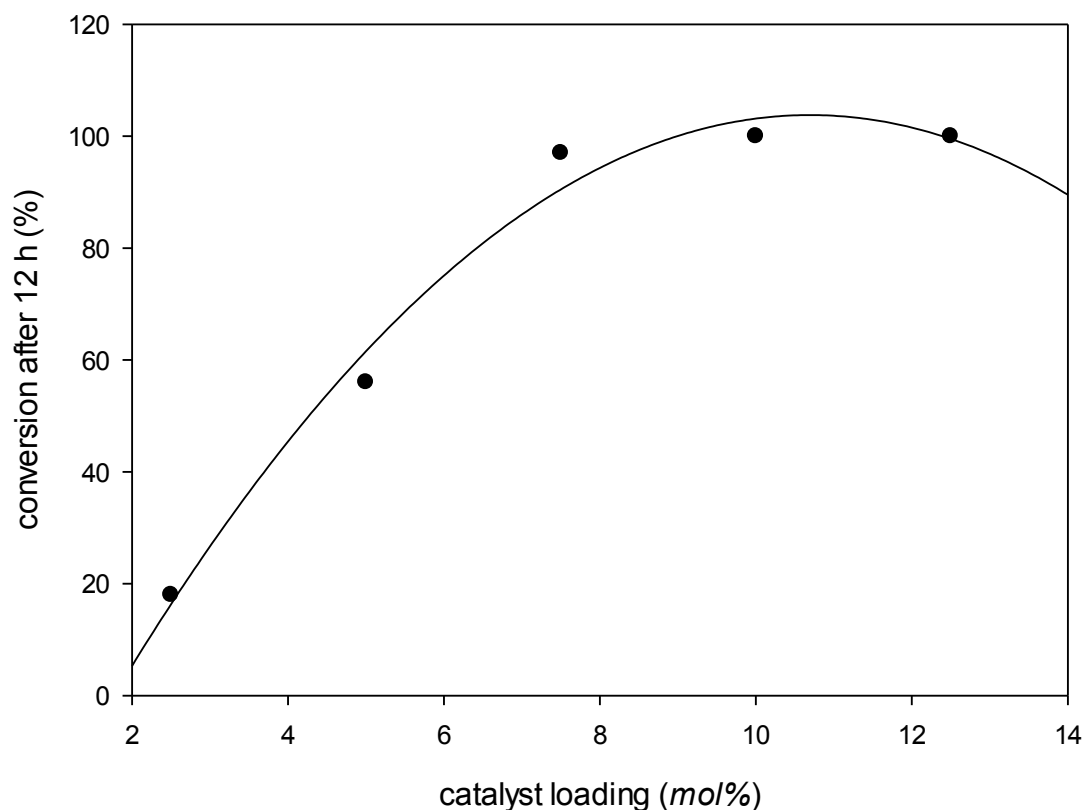
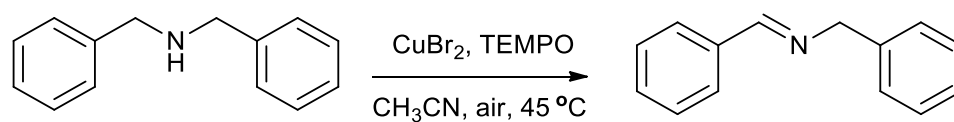


Figure S1. The effect of catalyst to substrate ration on the conversion for the oxidation of dibenzylamine. Reaction conditions: dibenzylamine (4 mmol), 9 ml CH_3CN , air (1 atm), 45°C , 12 h. Conversions were determined by GC using dodecane as an internal standard.

Kinetic study of the oxidation of dibenzylamine

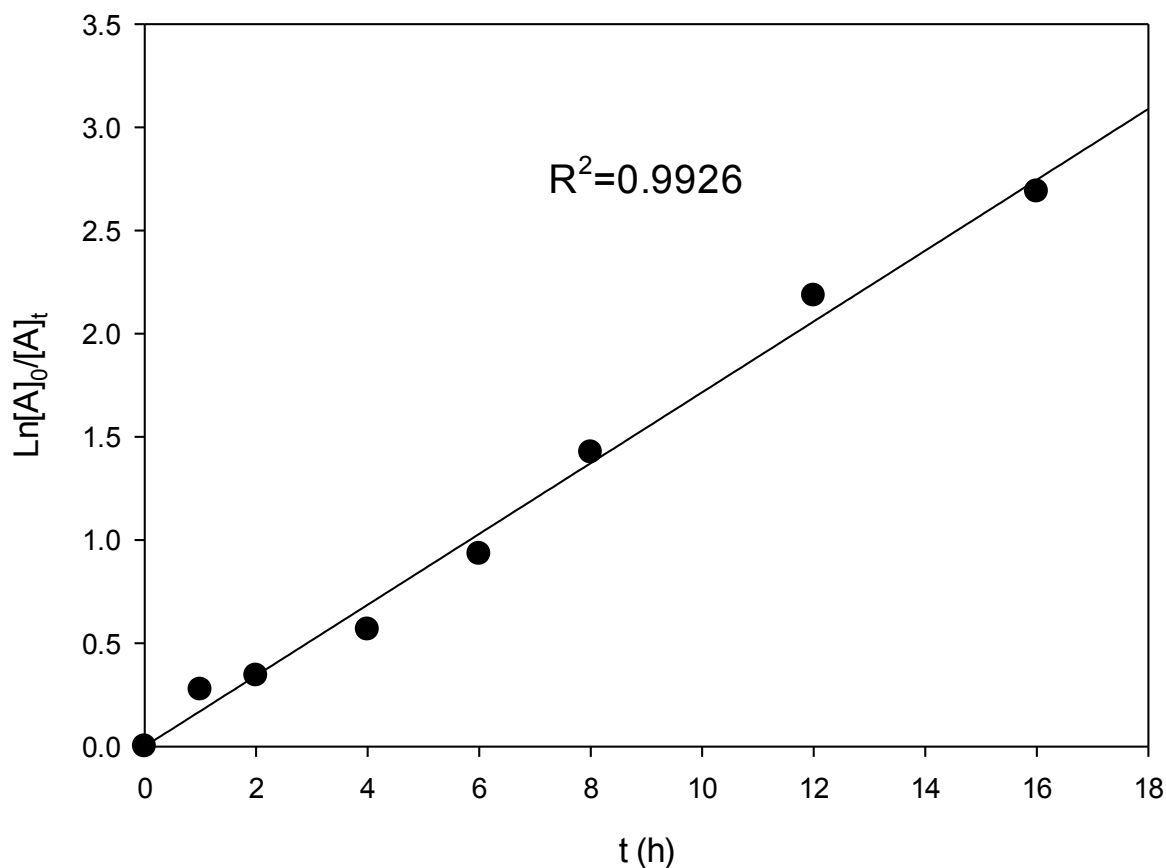
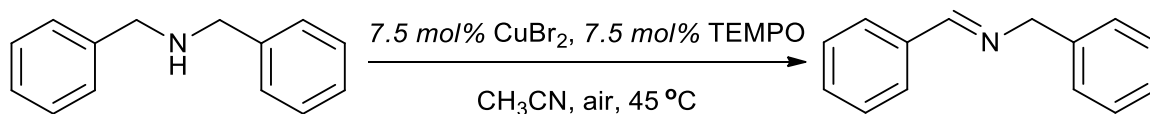


Figure S2. Time-dependence of substrate concentration for the oxidation of dibenzylamine. Reaction conditions: dibenzylamine (4 mmol), CuBr₂ (0.3 mmol), TEMPO (0.3 mmol), 9 ml CH₃CN, air (1 atm), 45 °C.

Kinetic studies showed a first-order dependence for the reaction rate on the dibenzylamine concentration. $k_{\text{obs}} = 0.17 \text{ h}^{-1}$.

