Supplementary Material (ESI) for Green Chemistry

Supplementary Information

Selective Synthesis of *N*-Aryl Hydroxylamines by the Hydrogenation of Nitroaromatics Using Supported Platinum Catalysts

Yasumasa Takenaka,*[a] Takahiro Kiyosu,[b] Jun-Chul Choi,[a] Toshiyasu Sakakura[a] and Hiroyuki Yasuda*[a]

[a] National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan

[b] Wako Pure Chemical Industries, Ltd., 1633 Matoba, Kawagoe, Saitama 350-1101, Japan

* Corresponding author. Tel: +81-29-861-4579 & Fax: +81-29-861-4580 (Y. Takenaka)

Tel: +81-29-861-9399 & Fax: +81-29-861-4580 (Y. Yasuda)

E-mail address: takenaka-yasumasa@aist.go.jp (Y. Takenaka), h.yasuda@aist.go.jp (H. Yasuda)

Reaction Condition of Selective Hydrogenation and Analytical Data of Products

Hydrogenation of Nitrobenzene Catalyzed by Pt/SiO_2 under 10 bar of H_2 (Table 1, entry 2).

Conditions: 10 mL autoclave, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), nitrobenzene (2 mmol), H_2 (10 bar), room temperature, 5 h, giving *N*-phenyl hydroxylamine (PHA) (73.2% HPLC yield, 75.4% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Pt/SiO_2 under 1 bar of H_2 (Table 1, entry 3).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 2 h, giving *N*-phenyl hydroxylamine (PHA) (7.2% HPLC yield, 98.6% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Pt/SiO_2 with NEt_3 (Table 1, entry 5).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), NEt_3 (0.36 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 2 h, giving *N*-phenyl hydroxylamine (PHA) (98.8% HPLC yield, 98.8% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Pt/C (Table 1, entry 7).

Conditions: 25 mL glass vessel, 5 wt% Pt/C (20 mg), isopropanol (2 mL), dimethyl sulfoxide (1.26 mmol), NEt_3 (0.072 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 2 h, giving PHA (97.2% HPLC yield, 97.2% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Pt/Al_2O_3 (Table 1, entry 8).

Conditions: 25 ml glass vessel, 5 wt% Pt/Al_2O_3 (20 mg), isopropanol (2 mL), dimethyl sulfoxide (1.26 mmol), NEt_3 (0.072 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 1.5 h, giving PHA (96.7% HPLC yield, 96.7% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Pt/SiO_2 (P) (Table 1, entry 9).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (P) (20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.84 mmol), NEt_3 (0.072 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 1.5 h, giving PHA (95.0% HPLC yield, 96.6% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Pd/SiO_2 (Table 1, entry 10).

Conditions: 25 mL glass vessel, 5 wt% Pd/SiO_2 (Escat^{TM} 1351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), NEt_3 (0.36 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 6 h, giving PHA (15.0% HPLC yield, 15.3% selectivity).

Selective Hydrogenation of Nitrobenzene Catalyzed by Ru/SiO_2 (P) (Table 1, entry 11).

Conditions: 25 mL glass vessel, 5 wt% Ru/SiO_2 (P) (20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), NEt_3 (0.36 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 12 h, giving PHA (9.0% HPLC yield, 90.0% selectivity).

Promote Effect of the Addition of Amines (^{n}BuNH$_2$) (Table 2, entry 7).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 1 h, giving PHA (77.5% HPLC yield, 99.0% selectivity).

Selective Hydrogenation of Nitrobenzene in Organic Solvents (THF) (Table 3, entry 5).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), THF (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 4.5 h, giving PHA (99.8% HPLC yield, 99.8% selectivity).

Selective Hydrogenation of Nitrobenzene in NEt_3 (Table 3, entry 11).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), NEt_3 (2 mL), dimethyl sulfoxide (0.42 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 8 h, giving PHA (94.4% HPLC yield, 99.9% selectivity).

Hydrogenation of Nitrosobenzene (Figure 2 (a)).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), nitrosobenzene (2 mmol), H_2 (1 bar), room temperature, 30 min, giving PHA (4.2% HPLC yield) and azoxybenzene (47.0% HPLC yield).

Hydrogenation of Nitrosobenzene with NEt_3 (Figure 2 (b)).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), NEt_3 (0.072 mmol), nitrosobenzene (2 mmol), H_2 (1 bar), room temperature, 30 min, giving PHA (5.8% HPLC yield) and azoxybenzene (47.0% HPLC yield).

Hydrogenation of Azoxybenzene.

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), NEt_3 (0.072 mmol), azoxybenzene (1 mmol), H_2 (1 bar), room temperature, 2 h. Azoxybenzene was not hydrogenated in this reaction conditions.

Selective Hydrogenation of 4-Cyano Nitrobenzene (Table 4, entry 1).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-cyano nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 95 min, giving 4-cyano-*N*-phenyl hydroxylamine (98% NMR yield, >99% selectivity). ^{1}H

NMR (400MHz, $CDCl_3$) in crude product: δ 5.22-6.18 and 6.93-7.00 (br, 2H, N*H*O*H*), 7.01 (d, $J_{H\text{-}H}$ = 8.9 Hz, 2H, C_6H_4), 7.75 (d, $J_{H\text{-}H}$ = 8.9 Hz, 2H, C_6H_4).

Selective Hydrogenation of 4-Methoxycarbonyl Nitrobenzene (Table 4, entry 2).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-methoxycarbonyl nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 95 min, giving 4-methoxycarbonyl-*N*-phenyl hydroxylamine (>99% NMR yield, >99% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 3.85 (s, 3H, CO_2CH_3), 6.98 (d, $J_{H\text{-}H}$ = 8.8 Hz, 2H, C_6H_4), 7.75-7.84 (br, 2H, N*H*O*H*), 7.89 (d, $J_{H\text{-}H}$ = 8.8 Hz, 2H, C_6H_4).

Purification by column chromatography on silica gel (Kanto Chemicals, silica gel 60 (spherical), 63-210 μm) using hexane/ethyl acetate (5/1 and 2/1 v/v) yielded 293 mg (88%) of 4-methoxycarbonyl-*N*-phenyl hydroxylamine (R_f = 0.30; hexane/ethyl acetate = 2/1 v/v) as a white solid. ^{1}H NMR (400MHz, $CDCl_3$): δ 3.89 (s, 3H, CO_2CH_3), 5.05-5.45 (br, 1H, NHO*H*), 6.99 (d, $J_{H\text{-}H}$ = 8.8 Hz, 2H, C_6H_4-N-*ortho*), 6.70-7.25 (br, 1H, N*H*OH), 7.97 (d, $J_{H\text{-}H}$ = 8.8 Hz, 2H, C_6H_4-N-*meta*). ^{13}C NMR (400MHz, $CDCl_3$): δ 51.85 (CO_2CH_3), 112.96 (C_6H_4-N-*ortho*), 123.34 (C_6H_4-C-*ipso*), 130.98 (C_6H_4-N-*ortho*), 153.88 (C_6H_4-N-*ipso*), 167.00 (CO_2CH_3). IR (KBr): 3341.8, 3248.7, 2956.5, 2360.0, 1929.8, 1684.4, 1603.9, 1582.2, 1514.2, 1489.1, 1436.1, 1406.6, 1374.8, 1323.2, 1293.3, 1261.5, 1198.8, 1172.8, 1125.5, 1026.2, 968.3, 897.9, 846.8, 773.5, 749.9, 702.1, 667.9, 625.0, 517.4, 501.5, 470.7 cm^{-1}.

Selective Hydrogenation of 4-Chloro Nitrobenzene (Table 4, entry 3).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-chloro nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 100 min, giving 4-chloro-*N*-phenyl hydroxylamine (98% NMR yield, 98% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 5.42-5.76 and 6.68-6.82 (br, 2H, N*H*O*H*), 6.93 (d, $J_{H\text{-}H}$ = 8.9 Hz, 2H, C_6H_4), 7.23 (d, $J_{H\text{-}H}$ = 8.9 Hz, 2H, C_6H_4).

Selective Hydrogenation of 4-Fluoro Nitrobenzene (Table 4, entry 4).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-fluoro nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 100 min, giving 4-fluoro-*N*-phenyl hydroxylamine (96% NMR yield, 99% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 5.44-5.65 and 6.67-6.79 (br, 2H, N*H*O*H*), 6.97 and 6.98-6.99 (m, 4H, C_6H_4).

Selective Hydrogenation of Nitrobenzene (Table 4, entry 5).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 105 min, giving *N*-phenyl hydroxylamine (97.3% HPLC yield, 98.7% selectivity; 98% NMR yield, 99%

selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 5.82-6.25 and 6.60-6.90 (br, 2H, N*H*O*H*), 6.96-7.01 (m, 3H, C_6H_5), 7.26-7.28 (m, 2H, C_6H_5).

Selective Hydrogenation of Nitrobenzene by recovered Pt/SiO_2 (Table 4, entry 6).

After the run of Table 4, entry 5, Pt/SiO_2 catalyst was separated from the product solution by filtration using a PTFE membrane filter (0.5 μm), washed with IPA (three times of 5 mL), and dried under reduced pressure at room temperature. The recovered Pt/SiO_2 catalyst (20 mg) was then placed in a glass vessel (25 mL) and air was replaced by an argon stream. A Teflon-coated magnetic stir bar, solvent (2 mL), DMSO (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), and nitroaromatics (2 mmol) were successively placed in the vessel, and the suspension was purged with hydrogen. Then, the reaction mixture was stirred (1500 rpm) under 1 bar of hydrogen at room temperature for 115 min, giving PHA (97.0% HPLC yield, 98.8% selectivity).

Selective Hydrogenation of 4-Vinyl Nitrobenzene (Table 4, entry 7).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-vinyl nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 180 min, giving 4-vinyl-*N*-phenyl hydroxylamine (97% NMR yield, 97% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 5.02 (dd, $J_{H\text{-}H}$ = 11.0, 1.1 Hz, 1H, CH=C*H*$_2$), 5.60 (dd, $J_{H\text{-}H}$ = 17.6, 1.1 Hz, 1H, CH=C*H*$_2$), 5.02 (dd, $J_{H\text{-}H}$ = 17.6, 11.0 Hz, 1H, C*H*=CH$_2$), 6.94 (d, $J_{H\text{-}H}$ = 8.6 Hz, 2H, C_6H_4), 7.31 (d, $J_{H\text{-}H}$ = 8.6 Hz, 2H, C_6H_4), 7.74-7.86 (br, 2H, N*H*O*H*).

Selective Hydrogenation of 4-Methyl Nitrobenzene (Table 4, entry 8).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-methyl nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 180 min, giving 4-methyl-*N*-phenyl hydroxylamine (97% NMR yield, 98% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 2.30 (s, 3H, C*H*$_3$), 5.22-5.57 and 6.63-6.82 (br, 2H, N*H*O*H*), 6.91 (d, $J_{H\text{-}H}$ = 8.5 Hz, 2H, C_6H_4), 7.09 (d, $J_{H\text{-}H}$ = 8.5 Hz, 2H, C_6H_4).

Selective Hydrogenation of 3-Methyl Nitrobenzene (Table 4, entry 9).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 3-methyl nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 150 min, giving 3-methyl-*N*-phenyl hydroxylamine (98% NMR yield, 98% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 2.29 (s, 3H, C*H*$_3$), 6.70-7.11 (br, 2H, N*H*O*H*), 6.76, 6.77 and 6.78 (m, 3H, C_6H_4), 7.13 (t, $J_{H\text{-}H}$ = 7.6 Hz, 1H, C_6H_4).

Selective Hydrogenation of 2-Methyl Nitrobenzene (Table 4, entry 10).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 2-methyl nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 300 min, giving 2-methyl-*N*-phenyl hydroxylamine (97% NMR yield, 97% selectivity). ^{1}H

NMR (400MHz, $CDCl_3$) in crude product: δ 2.15 (s, 3H, C*H*$_3$), 5.22-5.75 and 6.62-6.84 (br, 2H, N*H*O*H*), 6.90 (t, $J_{H\text{-}H}$ = 7.3, 7.2 Hz, 1H, C_6H_4), 7.08 (d, $J_{H\text{-}H}$ = 7.3 Hz, 1H, C_6H_4), 7.21-7.24 (m, $J_{H\text{-}H}$ = 7.3, 7.2 Hz, 2H, C_6H_4).

Selective Hydrogenation of 4-Methoxy Nitrobenzene (Table 4, entry 11).

Conditions: 25 mL glass vessel, 5 wt% Pt/SiO_2 (Escat^{TM} 2351: 20 mg), isopropanol (2 mL), dimethyl sulfoxide (0.42 mmol), *n*$BuNH_2$ (0.072 mmol), 4-methoxy nitrobenzene (2 mmol), H_2 (1 bar), room temperature, 300 min, giving 4-methoxy-*N*-phenyl hydroxylamine (96% NMR yield, 97% selectivity). ^{1}H NMR (400MHz, $CDCl_3$) in crude product: δ 3.79 (s, 3H, OC*H*$_3$), 5.58-5.85 and 6.54-6.80 (br, 2H, N*H*O*H*), 6.85 (d, $J_{H\text{-}H}$ = 8.9 Hz, 2H, C_6H_4), 7.00 (d, $J_{H\text{-}H}$ = 8.9 Hz, 2H, C_6H_4).