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Supplementary Material (ESI)

Facile heterogeneous catalytic hydrogenation of C=N and C=O bonds in neat water: anchoring of water-soluble metal complexes onto ion-exchange resins

Pierluigi Barbaro,* Luca Gonsalvi,*Antonella Guerriero and Francesca Liguori
Consiglio Nazionale delle Ricerche, Istituto di Chimica dei composti Organometallici, 50019 Sesto Fiorentino, Firenze (Italy)
Fax: +39 055 5225203
e-mail: pierluigi.barbaro@iccom.cnr.it , l.gonsalvi@iccom.cnr.it

General information

All reaction and manipulations were routinely performed under nitrogen by using standard schlenk techniques, unless stated otherwise. PTA was obtained as from literature procedure.[1] $[Ir(cod)_2]PF_6$ was synthesised as from literature procedure except for PF_6 counteranion.[2] All solvents were distilled and degassed prior to use according to standard procedures.[3] Doubly distilled water was used for solubility measurements. These were performed by gradual addition of water to 5 mg of the sample by microsyringe until complete dissolution, under mild stirring in a thermostated bath kept at 20 °C.

Deuterated solvents and other reagents such as 5-methylquinoxaline, 2-methylquinoxaline, 3,4-dihydroisoquinoline, 2,6-dimethylquinoline, harmaline , dihydro-4,4-dimethyl-2,3-furandione, $AgPF_6$ were reagent grade and were used as received for commercial suppliers without other purification.

Dowex 50Wx2-100 strong cation exchange resin [H^+-D50wx2, H^+form, 2% cross linked gel-type, 50-100 mesh, (150-297 μm) bead-size, 0,6 meq/ mL,- 4.8 meq/g exchange capacity, abbreviated as], was obtained from Aldrich (21-744-1)

$^{31}P\{^1H\}$ NMR spectra were recorded on a Bruker Avance DRX-300 spectrometer operating at 121.49 MHz or on a Bruker Avance II DRX-400 operating at 161.98 MHz. Chemical shift are relative to external 85% H_3PO_4 with downfield values reported as positive. ^1H-NMR were recorded at 300.13 MHz on a Bruker Avance DRX-300 spectrometer or at 400.13 MHz on a Bruker Avance II DRX-400.Chemical shift in ppm are relative to tetramethylsilane as external reference or calibrated against residual solvent resonance.$^{13}C\{^1H\}$ NMR were recorded at 100.613 MHz on a Bruker Avance DRX-400 spectrometer, chemical shift are calibrated against the deuterated solvent multiplet. CP-MAS ^{31}P NMR were recorded on a Bruker Avance DRX-400 spectrometer operating at 161.98 MHz, in a 4 mm sapphire rotor, at rotor speed of 8 KHz.

Elemental analyses were performed on a Perkin-Elmer 2400 series II elemental analyzer. ESI-MS spectra were measured on a LCQ Orbitrap mass spectrometer (ThermoFischer, San Jose, CA, USA) equipped with a conventional ESI source by direct injection of the sample solution and are reported in the form *m/z* (intensity relative to base = 100).

The metal content in the resin-supported catalysts was determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) with a Varian 720ES instrument coupled with an autosampler Agilent SP3 at a sensitivity of 0.500 ppm for solid samples. Each sample was treated in a microwave-heated digestion bomb (Milestone, ETHOS Start D labstation with easyWAVe or easyCONTROL software, and HPR1000/10S high pressure segmented rotor).

ESEM (environmental-scanning-electron-microscopy) measurements were performed on a FEI quanta200 microscope operating at 20 keV accelerating voltage in the low-vacuum mode (1torr), equipped with an EDAX- Energy Dispersive X-Ray spectrometer (EDS)].

Batch reactions under a pressure controlled of hydrogen were performed with a stainless steel autoclave (50 mL internal volume) constructed at ICCOM-CNR (Firenze- Italy) equipped with magnetic stirrer, a Teflon inset and flask, a temperature controller (PIXSYS ATR 110 or ATR121) and a pressure controller (DIGITRON P445). The heating was achieved by an oil bath with a temperature controller.

Catalytic flow hydrogenations were carried out using a continuous-flow reactor system constructed at Istituto di Chimica dei Composti OrganoMetallici, Sesto Fiorentino (Italy). The system was designed to allow for a simultaneous flow of substrate solution and hydrogen gas (up to 40 bar pressure). The reactor was completely inert, as all wet parts were made of PEEK, PFA or PFTE. The flow of the substrate solution was regulated by an Alltech® model 426 HPLC pump in PEEK. A constant flow of hydrogen gas was adjusted by a flow controller BRONKHORST HI-TEC model F200CV-002-RGD-11-V-MFC. The hydrogen pressure in the reactor was monitored by a BRONKHORST HI-TEC P502C-AGD-11-V-6K0R-EPC meter. The concurrent flows of gas and liquid were driven through a T-shaped PEEK mixer to ensure efficient gas dispersion. The mixed hydrogen-substrate solution stream was introduced in the reactor through a 6-port Rheodyne mod. 9060 switching valve in PEEK. The solid catalyst was pre-packed into a commercial Peek-Lined Column Hardware (30x2,1 mm) Grace & Co. equipped with 2µm PAT® frit insert at the entrance of the catalyst bed to ensure an optimum flow distribution. The system was equipped with a temperature controller (PIXSYS ATR121). At the outlet of the reactor, the product solution was collected for GC analysis and the excess amount of the hydrogen gas released to the atmospheric pressure. Commercially available H_2 (99.995%) was used as received.

GC-analyses were performed on a Shimadzu GC 2010 gas chromatograph equipped with flame ionization detector and a 30 m (0.25 mm i.d., 0.25 µm film thickness) SPB-1 Supelco fused silica capillary column and on a Shimadzu GC 2010-Plus gas chromatograph equipped with flame ionization detector and a 30 m (0.25 mm i.d., 0.25 µm film thickness) VF-WAXms fused silica capillary column, GC-MS analyses were performed on a Shimadzu QP5000 apparatus equipped with identical capillary columns.

Synthesis of [Ir(cod)(PTA)$_2$]PF$_6$ (1)

In a Schlenk tube kept under an inert atmosphere of nitrogen, PTA (0.14 g, 0.90 mmol) was dissolved in dichloromethane (10 mL) and added by cannula to a solution of [Ir(cod)$_2$]PF$_6$ (0.25 g, 0.45 mmol) in dichloromethane (15 mL). The reaction mixture was left stirring at room temperature for 1h 30 min, during which a pale yellow precipitate appeared. The compound was collected on G3 sintered-glass filter, washed with CH_2Cl_2 (2 x 1 mL), dried under a stream of nitrogen and stored under nitrogen. Yield 0.22 g (64%). $S(H_2O)_{20°C}$ = 1.85 g/L.

Anal. calcd. for $C_{20}H_{36}N_6P_3F_6Ir$ (759.67 g mol^{-1}): C, 31.62; H, 4.78; N, 11.06 %. Found: C, 32.08; H, 4.98; N, 10.91 %.

$^{31}P\{^1H\}$ NMR (161.98 MHz, acetone-d_6, 294 K): δ = -90.76 (2P, s, PTA), -144.24 (1P, sept, J_{PF} = 707.6 Hz PF$_6$). $^{31}P\{^1H\}$ NMR (161.98 MHz, D_2O, 294 K): δ = -86.88 (2P, s, PTA), -145.07 (1P, sept, J_{PF} = 708.6 Hz PF$_6$). CP MAS ^{31}P NMR (161.98 MHz, 294 K): δ = -87.3 (2P, PTA), -142.21 (1P, sept, PF$_6$).

^{1}H NMR (400.13 MHz, acetone-d_6, 294 K): δ = 2.24-2.35 (4H, m, CH$_2$, COD), 2.46-2.62 (4H, m, CH$_2$, COD), 3.74 (4H, br s, -CH=, COD), 4.30 (12H, br m, N-C$\underline{H}_2$-P), 4.61 (6H, AB System, J_{HAHB} = 12.7 Hz, N-C$\underline{H}_2$-N), 4.72 (6H, AB System, J_{HAHB} = 12.7 Hz, N-C$\underline{H}_2$-N). ^{1}H NMR (400.13 MHz, D_2O, 294 K) δ = 2.28-2.56 (8H, m, CH$_2$, COD), 3.71-3.84 (m, 4H, -C$\underline{H}$=, COD), 4.17 (12H, br s, N-C$\underline{H}_2$-P), 4.58-4.72 (12H, m, N-C$\underline{H}_2$-N).

$^{13}C\{^1H\}$ NMR (100.61 MHz; acetone-d_6, 294 K): δ = 33.97 (4C, t, H$\underline{C}$H, COD), 55.19 (3C, t, N-C$\underline{H}_2$-P) 66.284C, d, -$\underline{C}$H=, COD), 72.27 (3C, t, N-C$\underline{H}_2$-N)

MS(nESI$^+$): *m/z* 615.21 (100), 613.21 (55), 616.21 (19) [(COD)Ir(PTA)$_2$]$^+$.

CP MAS ^{31}P NMR data of resin-supported **1**:

Li-resin-**1**: CP MAS ^{31}P NMR (161.98 MHz, 294 K) δ = -83.2 (PTA)

H-resin-**1**: CP MAS ^{31}P NMR (161.98 MHz, 294 K) δ = -69.5 (PTA)

Pre-treating of the resin Dowex-H^+

The following operations were performed in air.

Commercial Dowex 50wx2-100 strong cation-exchange resin (H^+ form) (10 g) was washed with refluxing, deionized water for 3h and with methanol for 1h, using a Soxhlet apparatus. After cooling to room temperature, the resin was washed with dichloromethane at room temperature (2x100 mL), with methanol (2x100 mL), with diethylether (3x100 mL) and dried under a stream of nitrogen. The resin obtained (1.5 g) was stored under nitrogen.

Lithiation of the resin

The following operations were performed in air.

The resin, treated as previously described, (1.5 g) was added to a solution (1.0 M) of lithium hydroxide in deionized water (36 mL) and stirred with a an orbital stirrer at v = 190 rpm for 96 h.

The lithiated resin obtained (Li-D 50wx2) was washed repeatedly with deionized water until neutral pH of washings. The slurry was decanted, washed with methanol (3x100 mL), diethyl ether (3x 100 mL) dried in a stream of nitrogen and stored under nitrogen.

Immobilization of 1 on Resin-H^+-D50wx2

The following operations were performed under a nitrogen atmosphere.

To a degassed mixture of **1** (78 mg, 0.102 mmol) in a methanol: H_2O = 1:3 mixture (80 mL), dry Resin-H^+-D50wx2 (700 mg, 3.36 meq/SO_3^- H^+ group) was added. The mixture was degassed and stirred with an orbital stirrer (v = 190 rpm) at room temperature for 24 h. The resin obtained was decanted, washed with degassed H_2O (3x60 mL) then methanol (3x60 mL), finally with diethyl ether (3x60 mL), dried under a stream of nitrogen and stored under nitrogen.

ICP-OES analysis of the resin showed the Ir content to be 1.73% (w/w)

Immobilization of 1 on lithiated Resin-Li+-D50wx2

The following operations were performed under a nitrogen atmosphere.

To a degassed mixture of **1** (78 mg, 0.102 mmol) in a methanol: H_2O = 1:3 mixture (80 mL) was added dry Resin-Li^+-D50wx2 (700 mg, 3.36 meq/SO_3^- H^+ group).The mixture was degassed and stirred with an orbital stirrer (v = 190 rpm) at room temperature for 24 h. The resin obtained was decanted, washed with degassed H_2O (3x60 mL) then methanol (3x60 mL), finally with diethyl ether (3x60 mL), dried under a stream of nitrogen and stored under nitrogen.

ICP-OES analysis of the resin showed the Ir content to be 1.68% (w/w)

Determination of the metal-content in the resin-supported catalysts and in the heterogeneous catalysis solutions

The metal content in the resin-supported catalysts was determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) with a Varian 720ES instrument coupled with an autosampler Agilent SP3 at a sensitivity of 0.500 ppm for solid samples. Each sample (20-50 mg) was treated in a microwave-heated digestion bomb (Milestone, ETHOS Start D labstation with easyWAVe or easyCONTROL software, and HPR1000/10S high pressure segmented rotor) with concentrated HNO_3 65% and H_2O_2 30% in a ratio 7:1 v/v and analysed with a Microwave Program DG-CH-05 (20 min at 200 °C, up to 1000 watt). The content of metal leached in the heterogeneous catalysis solutions was determined using the same instrument. The aqueous solutions were analyzed directly after 1:5 or 1:10 dilution in acid, the methanol solutions were diluted with water before acid mineralization.

Characterization of heterogeneous catalyst by ESEM

ESEM Image of a 50WX2-Ir complex was obtained on a FEI quanta200 microscope operating at 20 keV accelerating voltage in the low-vacuum mode (1torr), equipped with an EDAX- Energy Dispersive X-Ray spectrometer (EDS).

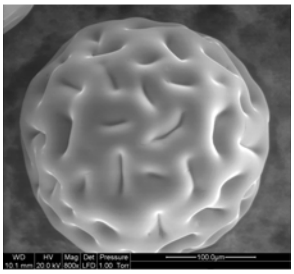

Fig. S1 ESEM image (secondary electrons, 800 magnifications, 20 keV, 1 torr) of a 50WX2-Ir complex

Homogeneous Hydrogenation Reaction of 2-methylquinoxaline with 1

In the homogeneous reaction, the autoclave was charged with **1** (4.1 mg catalyst, 5.5 x 10^{-3} mmol) to have a substrate/Ir = 150 ratio and degassed under a stream of nitrogen. A solution of substrate (0.107 mL; 0.83 mmol) in nitrogen-degassed water (12 mL) was then transferred via a Teflon capillary into the autoclave under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The reactor was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h, then left stirring with magnetic stirrer for 16 h at this temperature. After 16h the reactor was depressurized and a sample of the reaction mixture was analyzed by GC. Total conversion: 91.1 %; selectivity to 2-Me-1,2,3,4-tetrahydroquinoxaline = 100%

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column). [Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115°C (12 min) ---gradient 5 °C/min--- 180 °C (10min); Linear velocity: 32 cm/sec

Heterogeneous Hydrogenation Reaction of 2-methylquinoxaline with 1 /DowexH$^+$

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H$^+$-D50wx2 (Ir = 1.73% w/w) (61 mg catalyst, 5.5 x 10^{-3} mmol Ir), to have a substrate/Ir = 150 ratio, was placed under nitrogen into a stainless steel autoclave and was degassed under a stream of nitrogen.

A solution of 2-methylquinoxaline (0.107 mL; 0.83 mmol) in nitrogen-degassed water (12 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h and stirred with orbital stirrer for 22h at 80 °C. After that time, the reactor was cooled and depressurized. A sample of this solution (0.5 µL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis (0.2 ppm).

Total conversion: 92.2 %; selectivity to 2-Me-1,2,3,4-tetrahydroquinoxaline = 100%

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column).

[Conditions: Temp. inj. = 250 °C; Temp. Det. = 300°C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 180 °C (10min); Linear velocity: 32 cm/sec

Heterogeneous Hydrogenation Reaction of 2-methylquinoxaline with 1 /DowexH$^+$ -recycling experiments

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H$^+$-D50wx2 (Ir = 1.73% w/w) (61 mg catalyst, 5.5 x 10^{-3} mmol Ir), to have a substrate/Ir = 150 ratio, was placed under nitrogen into a stainless steel autoclave and it was degassed under a stream of nitrogen.

A solution of 2-methylquinoxaline (0.107 mL; 0.83 mmol) in nitrogen-degassed water (12 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h and stirred with orbital stirrer for 22h at this temperature. After that time, the reactor was cooled, depressurized under a hydrogen stream and the solution was removed with a gas-tight syringe. A sample of this solution (0.5 μL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-AES analysis.

Recycling experiments were performed as follows: a hydrogen-degassed solution of the substrate (0.107 mL, 0.83 mmol) in bi-distilled water (12 mL) was transferred via a Teflon® capillary under a stream of hydrogen, into the autoclave containing the catalysts after its use in the previous hydrogenation reaction. The reactor was charged with H_2 (20 bar), heated to 80 °C over 1h and the solution stirred for 22h at this temperature. After that time, the autoclave was cooled, depressurized under a hydrogen stream and the solution was removed with a gas-tight syringe. A sample of this solution (0.5 μL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis.

Representative data for 4 recycling experiments were reported in Table 4 in the main text.

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column). [Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 180 °C (10min); Linear velocity: 32 cm/sec

Homogeneous Hydrogenation Reaction of 5-methylquinoxaline with 1

In the homogeneous reaction, the autoclave was charged with **1** (4.1 mg catalyst, 5.5 x 10^{-3} mmol Ir) to have a substrate/Ir = 150 ratio and degassed under a stream of nitrogen. A solution of substrate (0.106 mL; 0.825 mmol) in nitrogen-degassed water (10 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h and the solution stirred with magnetic stirrer at 80 °C for 17 h. After 17h the reactor was depressurized. A sample of reaction mixture was analyzed by GC. Total conversion: 32 %; selectivity to 5-Me-1,2,3,4-tetrahydroquinoxaline = 100%

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column). [Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 180 °C (10min); Linear velocity: 32 cm/sec

Heterogeneous Hydrogenation Reaction of 5-methylquinoxaline with 1 /DowexH$^+$

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H$^+$-D50wx2 (Ir = 1.73% w/w) (61 mg catalyst, 5.5 x 10^{-3} mmol Ir) to have a substrate/Ir =150 ratio, was placed under nitrogen into a stainless steel autoclave and was degassed under a stream of nitrogen. A solution of 5-methylquinoxaline (0.106 mL; 0.825 mmol) in nitrogen-degassed water (10 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h and the solution was stirred with orbital stirrer for 22 h at this temperature. After that time, the reactor was cooled and depressurized. A sample of this solution (0.5 μL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis. (0.32 ppm)

Total conversion: 89.2 % ; selectivity to 5-Me-1,2,3,4-tetrahydroquinoxaline = 100%

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column). [Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 180 °C (10min); Linear velocity: 32 cm/sec

Homogeneous Hydrogenation Reaction of 3,4-dihydroisoquinoline with 1

In the homogeneous reaction, the autoclave was charged with **1** (2.08 mg catalyst, 2.75 x 10^{-3} mmol Ir) to have a substrate/Ir = 305 ratio and degassed under a stream of nitrogen. A solution of substrate (0.108 g, 0.825 mmol) in nitrogen-degassed water (15 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), and the solution was stirred with magnetic stirrer to 80 °C for 1h. After 1h the reactor was depressurized. A sample of reaction mixture was analyzed by GC.

Total conversion: 11.0 %; selectivity to 1,2,3,4-tetrahydroisoquinoline = 100%
GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column).
[Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 250 °C (20min); Linear velocity: 32 cm/sec

Heterogeneous Hydrogenation Reaction of 3,4-dihydroisoquinoline with 1 /DowexH$^+$

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H$^+$-D50wx2 (Ir = 1.73% w/w) (30.5 mg catalyst, 2.75 x 10^{-3} mmol Ir), to have a substrate/Ir = 305 ratio, was placed under nitrogen into a stainless steel autoclave and it was degassed under a stream of nitrogen. A solution of substrate (0.108 g; 0.825 mmol) in nitrogen-degassed water (15 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), and the solution was stirred to 80 °C with orbital stirrer for 1h.
After that time, the reactor was cooled and depressurized. A sample of this solution (0.5 μL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis (7.6 ppm)
Total conversion: 99.9 %; selectivity to 1,2,3,4-tetrahydroisoquinoline = 100%
Different Substrate/Ir ratios and different reaction times were used to tests catalysts activity (see Table 2 and Table 3 in the main text)
GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column).
[Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 250 °C (20min); Linear velocity: 32 cm/sec

Leaching Tests

In a typical experiment, the leaching test was performed as follows. After the desired time, the autoclave containing the hydrogenation reaction mixture was cooled, depressurized and the solution recovered by decantation under of stream of H_2 and analyzed for conversion by GC. An identical amount of the starting substrate was then added under H_2 and the mixture analyzed again by GC. The solution obtained was transferred into an autoclave under a hydrogen atmosphere. The reactor was then pressurized with hydrogen, heated and stirred under the same experimental conditions of the hydrogenation reaction using the immobilized catalyst. After the desired time (2-20 h, depending on the substrate), the autoclave was cooled and depressurized and a sample of the solution (0.5 μL) was analyzed by gas chromatography for conversion determination.

Heterogeneous Hydrogenation Reaction of 3,4-dihydroisoquinoline with 1 /DowexH$^+$ in Flow-reactor

In a continuous-flow reaction, the solid catalyst (23.0 mg catalyst **1** on Resin-H$^+$-D50wx2, 2.07 x 10^{-3} mmol Ir) was pre-packed into a commercial Peek-Lined Column (30x2.1 mm) equipped with a 2μm PAT® Frit/insert at the entrance of the catalyst bed to ensure an optimum flow distribution and the column was connected, under a nitrogen-stream, to the reactor pipes. The concurrent flows of hydrogen (4ml/min, pressure H_2 at reactor inlet= 17.2 bar) and of substrate solution (0.05M in water; Flow 0.12 mL/min), were driven through a T-shaped PEEK mixer to ensure efficient gas dispersion and the mixed hydrogen-substrate solution stream was introduced in the Peek-column. The system was heated to 80 °C and maintened at this temperature with a temperature controller.
At the outlet of the reactor, the product solution was collected (0.5 μL) for GC analysis. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis (3.8 ppm) (see Fig. 2 in the main text)
GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column).
[Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 250 °C (20min); Linear velocity: 32 cm/sec

Homogeneous Hydrogenation Reaction of Harmaline with 1

In a homogeneous reaction, the autoclave was charged with **1** (2.08 mg catalyst, 2.75 x 10^{-3} mmol Ir) to have a substrate/Ir = 100 ratio and degassed under a stream of nitrogen. A solution of substrate (0.059 g, 0.276 mmol) in a nitrogen-degassed mixture of MeOH:H_2O = 1:1.5 (18 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h and the solution was stirred with magnetic stirrer at this temperature for 22 h. After that time the reactor was cooled and depressurized. A sample of reaction mixture was analyzed by GC.

Total conversion: 99.3 %; selectivity to tetrahydro-β-carboline (Leptaflorine) = 96.7 %

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column).

[Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 130 °C (5 min) ---gradient 5 °C/min--- 250°C (20min); Linear velocity: 32 cm/sec

Heterogeneous Hydrogenation Reaction of Harmaline with 1 /DowexH$^+$

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H$^+$-D50wx2 (Ir = 1.73% w/w) (30.5 mg catalyst, 2.75 x 10^{-3} mmol Ir), to have a substrate/Ir = 100 ratio, was placed under nitrogen into a stainless steel autoclave and was degassed under a stream of nitrogen. A solution of substrate (0.059 g; 0.276 mmol) in a nitrogen-degassed mixture of MeOH:H_2O = 1:1.5 (18 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C over 1h and the solution was stirred with magnetic stirrer at this temperature for 24 h. After that time, the reactor was cooled and depressurized. A sample of this solution (0.5 μL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis (8.5 ppm).

Total conversion: 99.1 %; selectivity to tetrahydro-β-carboline (Leptaflorine) = 91.8 %

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column). [Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 130 °C (5 min) ---gradient 5 °C/min--- 250 °C (20min); Linear velocity: 32 cm/sec

Homogeneous Hydrogenation Reaction of 2,6-dimethylquinoline with 1

In a homogeneous reaction, the autoclave was charged with **1** (4.1 mg catalyst, 5.5 x 10^{-3} mmol Ir) to have a substrate/Ir = 50 ratio and degassed under a stream of nitrogen. A solution of substrate (0.043 g, 0.276 mmol) in a nitrogen-degassed MeOH:H_2O = 1:4 mixture (12.5 mL) was then transferred via a Teflon capillary into the autoclave under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (50 bar)/depressurization. The reactor was finally charged with a pressure of H_2 (50 bar), heated to 80 °C over 1h and stirred with magnetic stirrer at this temperature for 29 h. After that time the reactor was cooled and depressurized. A sample of reaction mixture was analyzed by GC.

Total conversion: 3.5 %; selectivity to 2,6-dimethyl-1,2,3,4-tetrahydroquinoline = 100 %

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column).

[Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 250 °C (15 min); Linear velocity: 32 cm/sec

Heterogeneous Hydrogenation Reaction of 2,6 dimethylisoquinoline with 1 /DowexH$^+$

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H$^+$-D50wx2 (Ir = 1.73% w/w) (61 mg catalyst, 5.5 x 10^{-3} mmol Ir) to have a substrate/Ir = 50 ratio was placed under nitrogen into a stainless steel autoclave and was degassed under a stream of nitrogen. A solution of substrate (0.043 g; 0.276 mmol) in a nitrogen-degassed MeOH:H_2O = 1:4 mixture (12.5 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (50 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (50 bar), heated to 80 °C over 1h and stirred with magnetic stirrer at this temperature for 29 h. After that time, the reactor was cooled and depressurized. A sample of this solution (0.5 μL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis(0.08 ppm)

Total conversion: 26.0 %; selectivity to 2,6-dimethyl-1,2,3,4-tetrahydroquinoline = 57.4 %

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (SPB-1 Supelco fused silica capillary column). [Conditions: Temp. inj. = 250 °C; Temp. Det. = 300 °C; Gas Aux. Helium] Column temperature 115 °C (12 min) ---gradient 5 °C/min--- 250 °C (15 min); Linear velocity: 32 cm/sec

Homogeneous Hydrogenation Reaction of dihydro-4,4'-dimethyl-2,3-furandione with 1

In the homogeneous reaction, the autoclave was charged with **1** (4.1 mg catalyst, 5.5 x 10^{-3} mmol Ir) to have a substrate/Ir = 100 ratio and degassed under a stream of nitrogen. A solution of substrate (0.070 g, 0.55 mmol) in a nitrogen-degassed water (13 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (20 bar), heated to 80 °C and was stirred with magnetic stirrer at this temperature for 4 h. After that time the autoclave was cooled and depressurized. A sample of reaction mixture was analyzed by GC.

Total conversion: 99.9 %; selectivity to (+/-)-pantolactone = 100 %

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (VF-WAXms)

[Conditions: Temp. inj. = 250 °C; Temp. Det. = 280 °C; Gas Aux. Helium] Column temperature 80 °C (5 min) ---gradient 5 °C/min--- 220 °C (15 min); Linear velocity: 25 cm/sec

Heterogeneous Hydrogenation Reaction of dihydro-4,4'-dimethyl-2,3-furandione with 1 /DowexH

In the heterogeneous reaction, the catalyst precursor **1** tethered on Resin-H^+-D50wx2 (Ir = 1.73% w/w) (61 mg catalyst, 5.5 x 10^{-3} mmol Ir), to have a substrate/Ir =100 ratio, was placed under nitrogen into a stainless steel autoclave and was degassed under a stream of nitrogen.

A solution of substrate (0.070 g; 0.55 mmol) in nitrogen-degassed water (13 mL) was then transferred via a Teflon capillary into the reactor under nitrogen. Nitrogen was replaced with hydrogen with 3 cycles of pressurization (20 bar)/depressurization. The autoclave was finally charged with a pressure of H_2 (50 bar), heated to 80 °C and stirred with magnetic stirrer at this temperature for 4 h. After that time, the reactor was cooled and depressurized. A sample of this solution (0.5 µL) was analyzed by gas chromatography to determine the conversion and selectivity. The remaining solution aliquot was analyzed for the determination of the amount of metal leached into solution via ICP-OES analysis(0.37 ppm)

Total conversion: 89.0%; (+/-)-pantolactone = 100 %

GC analyses: Shimadzu GC 2010 Plus gas chromatograph (VF-WAXms [Conditions: Temp. inj. = 250°C; Temp. Det. = 280°C; Gas Aux. Helium] Column temperature 80 °C (5 min) ---gradient 5 °C/min--- 220 °C (15 min); Linear velocity: 25 cm/sec

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Table **1S** Activity of Ir complex catalysts in hydrogenation reactions[a]

Substrate	Phase	Yield (%)	TOF (h^{-1})	Product	Selectivity (%)	Leaching (ppm)[i]
2-methylquinoxaline	Hetero[b]	92.2	6	2-methyl-1,2,3,4-tetrahydroquinoline	100	0.2
	Homo[b]	91.1	9	“	100	-
5-methylquinoxaline	Hetero[c]	89.2	6	5-methyl-1,2,3,4-tetrahydroquinoline	100	0.32
	Homo[c]	32.0	3	”	100	-
2,6-dimethylquinoline	Hetero[d]	26.0	1	2,6-dimethyl-1,2,3,4-tetrahydroquinoline	100	0.08
	Homo[d]	3.5	1	”	100	-
3,4-dihydroisoquinoline	Hetero[e]	99.9	300	1,2,3,4-tetrahydroisoquinoline	100	7.6
	Homo[e]	11.0	34	”	100	-
	Hetero[g]	89.7	374	”	100	4.0
Harmaline	Hetero[f]	99.1	4	leptaflorine	100	8.5
	Homo[f]	99.3	5	”	100	-
4,4’-dimethylfuran-2,3-dione	Hetero[h]	89.0	22	pantolactone	100	0.37
	Homo[h]	99.9	25	”	100	-

[a] Experimental conditions: P = 20 bar H_2, T = 80 °C; [b] H_2O, S/C = 150, Hetero (22h), Homo (16h); [c] H_2O, S/C = 150, Hetero (22h), Homo (17h); [d] 50 bar H_2, H_2O: MeOH = 4:1, S/C = 50, Hetero (29h), Homo (29h); [e] H_2O, S/C = 305, Hetero (1h), Homo (1h); [f] H_2O:MeOH = 1.5:1, S/C = 100, Hetero (24h), Homo (22h); [g] H_2O, S/C = 830, Hetero (2h), Homo (2h); [h] H_2O, S/C = 100, Hetero (4h), Homo (4h); [i] determined by ICP-OES.