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Highly Efficient, Recyclable Pd(II) Catalysts with Bisimidazole Ligands for the Heck Reaction in Ionic Liquids

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Supporting Information

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Experimental Procedures

General. Unless otherwise indicated, all starting materials were obtained from commercial suppliers (Aldrich, Lancaster, Strem, EM Science) and were used without further purification. THF was distilled over sodium/benzoketal, dichloromethane was also distilled over calcium hydride prior to use. All reactions were performed under an atmosphere of dry nitrogen. Analytical thin-layer chromatography (TLC) was performed on silica gel 60 F₂₅₄ pre-coated aluminum sheets from EM Science. Visualization was performed with a 254 nm ultraviolet lamp. Silica gel column chromatography was carried out with silica gel (60, 230-400 mesh) from EM Science. The ¹H and ¹³C NMR spectra were recorded on a Varian Gemini 200 MHz and a Bruker 300 MHz spectrometer. Chemical shifts were recorded in ppm (δ) relative to tetramethylsilane (TMS), and *J* values are given in Hertz. Chemical shifts in ¹³C NMR were measured relative to CDCl₃. Infrared spectra were recorded on a Shimadzu FTIR-8400S spectrophotometer and are recorded in wavenumbers (cm⁻¹). Mass spectra were obtained on a VG 7070E spectrometer. Ionic liquid [bmim][PF₆]¹ was prepared according to the reported procedure. All products are known compound and were identified by ¹H NMR, ¹³C NMR, MS and IR and comparison with literature data.

Synthetic Procedure for the Bisimidazole Ligand

In a 50 mL of round bottom flask, N-Methylimidazole (410 mg, 3 mmol) was dissolved in 20 mL of THF. After cooled to -30 °C, Methyl lithium (1.6 M solution, 2.4 mL) was dropwise for 20 min. and then stirred for 30 min. Iodine (910 mg, 3.6 mmol) was added to reaction mixture for one portion. Slowly evaluated temperature to room temperature, and stirred for additional 4 h. After checking TLC, 5 mL of saturated sodium thiosulfate solution was added, then extracted with 10 mL of methylene chloride (3 times). Organic layer was dried with magnesium sulfate, then evaporated all of solvents. The desired product was isolated by silica gel column chromatography as off-white solid (560 mg). (*R*_f = 0.65, CH₂Cl₂ : MeOH = 10 : 1) ¹H NMR (200 MHz, CDCl₃) : 3.58 (s, 3H), 6.95 (s, 1H), 7.05 (s, 1H), ¹³C (200MHz, CDCl₃) : 34.14, 120.42, 125.64, 135.44; EI MS (*m/z*) 208 [M⁺].

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In a 50 mL of round bottom flask, 2-Iodo-N-methylimidazole (1030 mg, 5 mmol) and Copper metal (630 mg, 10 mmol) were dissolved in 10 mL of DMF. After 2 h refluxed, the reaction mixtures were cooled to room temperature and then poured into 50 mL of water. The reaction mixture was extracted with dichloro methane (20 mL X 3) and then dried over magnesium sulfate, filtered, and concentrated in rotary evaporator. The desired product was isolated by silica gel column chromatography as off-white solid (320 mg). (R_f = 0.44, CH_2Cl_2 : MeOH = 10:1) ^1H NMR (200 MHz, CDCl_3) : 4.01 (s, 3H), 6.85 (s, 1H), 7.05 (s, 1H), ^{13}C (200MHz, CDCl_3) : 35.14, 122.43, 127.61, 138.44; EI MS (m/z) 162 [M^+].

General Procedure for the catalysts synthesis (1a)

In a 25 mL of round bottom flask, bis-N-methylimidazole (65 mg, 0.4 mmol) and (cod) $\text{PdCl}(\text{CH}_3)_2$ (106 mg, 0.4 mmol) were dissolved in 10 mL of DMC. After 2 h stirring at room temperature, the reaction mixtures were filtered with Celite. The remaining organic layer was concentrated *in vacuo*. The resulting solid was washed with anhydrous ethyl ether (10 mL X 3). The solid was dried *in vacuo* overnight (122 mg). ^1H NMR (200 MHz, CDCl_3) : 0.76 (s, 3H), 4.01-4.08 (q, J = 18.67 Hz, 6H), 6.78-6.87 (m, 3H), 7.19 (d, J = 1.4 Hz, 1H), ^{13}C (300MHz, $\text{DMSO}-d_6$) : 0.52, 36.20, 36.74, 123.68, 124.49, 125.11, 130.17, 130.29, 134.97, 137.21; EI MS (m/z) 318 [M^+].

General Procedure for the coupling reaction of iodoarenes with n-butyl acrylate.

In a 20 mL of round bottom flask was placed 2 g of [bmim][PF_6] and Pd(II) (19 mg, 0.06 mmol) were degassed under reduced pressure at 80 °C for 30 min, and then nitrogen gas was introduced. To the solvent was added triethylamine (0.63 mL, 4.5 mmol), 4-iodoanizole (702 mg, 3mmol) and n-butylacrylate (0.54 mL, 3.75 mmol), and the resulting mixture was heated, using an oil bath, at 120 °C (bath temp.) for 1 h. The product was extracted from the reaction mixture by addition of ethyl ether (10 mL), followed by decanting off an ethyl ether solution of the product. This was repeated three times and the ammonium salt was removed by extraction with water (5 mL X 2). The combined organic layer was concentrated by rotary evaporation. The desired product

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was isolated by short-path silica gel column chromatography. The identity of Heck coupling products was confirmed by comparison with literature spectroscopic data.

Table 1, Table 2 : *trans*-cinnamic acid *n*-butyl ester³

Table 3 Entry 1 : Thiophene-2-(*E*)-propenyl *n*-butyl ester⁴

Table 3 Entry 2 : 4-Methoxy- *trans*-cinnamic acid *n*-butyl ester⁴

Table 3 Entry 3 : 2-Methoxy- *trans*-cinnamic acid *n*-butyl ester⁵

Table 3 Entry 4 : 2-Isopropyl- *trans*-cinnamic acid *n*-butyl ester⁶

Table 3 Entry 5 : 2,6-Dimethyl- *trans*-cinnamic acid *n*-butyl ester⁷

Table 3 Entry 6 : 4-Methy- *trans*-cinnamic acid *n*-butyl ester and 4-Etyly- *trans*-cinnamic acid *n*-butyl ester⁸

Table 3 Entry 7 : 2-Bromo- *trans*-cinnamic acid *n*-butyl ester⁹ and 2-Iodo- *trans*-cinnamic acid *n*-butyl ester⁹

Table 3 Entry 8 : 2-Chloro- *trans*-cinnamic acid *n*-butyl ester¹⁰

Table 3 Entry 9 : 3-Chloro- *trans*-cinnamic acid *n*-butyl ester¹¹

Table 3 Entry 10 : 4-Trifluoromethyl- *trans*-cinnamic acid *n*-butyl ester¹²

Table 3 Entry 11 : 4-Nitro- *trans*-cinnamic acid *n*-butyl ester¹³

Table 3 Entry 2 : 4-Bromo- *trans*-cinnamic acid *n*-butyl ester¹¹

Table 4 Entry 1 : : *trans*-cinnamic acid *n*-butyl ester³

Table 4 Entry 2 : 4-Trifluoromethyl- *trans*-cinnamic acid *n*-butyl ester¹²

Table 4 Entry 3 : 4-Methy- *trans*-cinnamic acid *n*-butyl ester⁸

Table 4 Entry 4 : 4-Nitro- *trans*-cinnamic acid *n*-butyl ester¹³

Table 4 Entry 5 : 4-Methoxy- *trans*-cinnamic acid *n*-butyl ester⁴

Scheme 2

X=O (Coumarin)¹⁴, X = NH (Lactam)¹⁵

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Table 5, Entry 1 : 4-Methoxy- *trans*-cinnamic acid methyl ester¹⁶

Table 5, Entry 2 : 4-Methoxy- *trans*-cinnamic acid *t*-butyl ester¹⁷

Table 5, Entry 3 : 4-Methoxy- *trans*-cinnamic acid *n*-butyl ether¹⁸

Table 5, Entry 4 : 4-Methoxy- *trans*-styrene¹⁹

Table 5, Entry 5 : 4-Methoxy-4'-chloro *trans*-styrene²⁰

Table 6, Entry 1,2,3 : β,β -Diphenyl-*n*-butyl acrylate²¹

Table 6, Entry 4 : β,β -4,4'-Dimethoxydiphenyl-*n*-butyl acrylate²¹

Table 6, Entry 5 : β,β -4,4'-Dimethyldiphenyl-*n*-butyl acrylate²¹

Table 6, Entry 6 : β,β -4,4'-Difluoromethyldiphenyl-*n*-butyl acrylate²¹

Table 6, Entry 7 : β,β -4-Methyldiphenyl-*n*-butyl acrylate²²

Table 6, Entry 8 : β,β -Acetyldiphenyl-*n*-butyl acrylate²¹

Procedure for the catalyst recycling study

After reaction, the product was extracted from the reaction mixture with ethyl ether (10 mL X 3), and the ammonium salt was removed by extraction with water (5mL X 2). Excess ethyl ether and water were removed under reduced pressure at 80 °C for 30 min., the remaining ionic liquid was used for the next cycle.

Figure 1. Time Conversion of Heck Reaction with 4-Iodoanisole and *n*-Butyl acrylate

Condition : 3 mmol of 4-Iodoanisole, 1.25 eq of *n*-Butyl acrylate , 1.5 eq. of Et₃N, 2 mol % of **1a**. 2 g of [bmim]PF₆, 120 °C, The conversion of (*E*)-cinnamate was calculated by ¹H NMR.

Scheme 2. Synthesis of a Coumarin and a Lactam by the Heck Reaction^a

^a Conditions : (a) 3 mmol of iodoarenes, 1.2 eq. of acrylate, 1.5 eq. of Et₃N, 2 mol% of **1a**, 2 g of ionic liquid, 120 °C, 1 h. (b) HOCH₂CH₂OH, 200 °C, 12 h

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