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JOURNAL OF THE CHINESE
CHEMICAL SOCIETY

A Reusable Palladium(II)/Cationic 2,2′-Bipyridyl Catalytic System for Hydroxycarbonylation of Aryl Iodides in Water

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(Received: Nov. 14, 2012; Accepted: Dec. 28, 2012; Published Online: Feb. 1, 2013; DOI: 10.1002/jccs.201200595)

A water-soluble palladium(II)/cationic 2,2′-bipyridyl system was utilized to catalyze hydroxycarbonylation of aryl iodides in the presence of a pressurized CO atmosphere under a basic aqueous solution at 100 °C. The residual aqueous solution could be reused in several times with only a slight decrease in catalytic activity. Thus, it reduced wastage of the precious metal in the reaction. A variety of aromatic carboxylic acids could still be obtained in high yields with the catalytic amount to 0.01 mol%.

Keywords: Reusable catalyst; Palladium; Cationic 2,2′-bipyridyl; Hydroxycarbonylation; Water.

INTRODUCTION

Palladium-catalyzed hydroxycarbonylation of aryl halides in the presence of a carbon monoxide atmosphere is a common method for the preparation of aromatic carboxylic acids.[1] Generally, a basic aqueous–organic two–phase solvent system is used for the reaction, which may lead to difficult separation and recycling of the catalyst from the product for the further reuse.[2] Therefore, a reusable palladium catalyst for hydroxycarbonylation of aryl halides is highly valuable with regards to economic and environmental concerns. Leadbeater's group reported microwave-promoted hydroxycarbonylation of aryl iodides catalyzed by palladium salts in water with loading amounts of either 0.01 mol% or 1 mol%; however, the reuse of the catalyst was not studied.[3] An amphiphilic resin-supported phosphine-palladium complex[4] and a nanoparticle-supported palladium complex[5] can serve as recyclable catalysts for the hydroxycarbonylation of aryl halides under aqueous alkaline conditions, but a high catalyst loading (3 and 2 mol%, respectively) is required for the reactions. Recently, ionic liquids have also been employed as green solvents for palladium-catalyzed hydroxycarbonylation of aryl halides for the purpose of reuse.[6] In these reactions, an excess amount of water is still required. A basic aqueous environment is necessary for Pd-catalyzed hydroxycarbonylation of aryl halides. Hence, it would be useful to develop a water-soluble, highly efficient and reusable palladium catalytic system to achieve hydroxycarbonylation of aryl halides using neat water as the reaction medium, in which there is no need to separate the catalyst from the aqueous phase for reuse.

We have recently utilized $PdCl_2(NH_3)_2$ to associate with cationic 2,2′-bipyridyl ligand (Figure 1, denoted **L**) to form a water-soluble catalytic system for C–C bond coupling reactions in water under air.[7] As part of our continuing studies on this highly efficient and reusable catalytic system, we report here that our catalytic system can not only catalyze hydroxycarbonylation of aryl iodides, giving high yields of aromatic carboxylic acids at a very low catalyst loading level, but can also be reused several times with only a slight decrease in activity, rendering this hydroxycarbonylation reaction green and economic.

EXPERIMENTAL

General. All chemicals were purchased from commercial suppliers and were used without further purification. The cationic 2,2′-bipyridyl ligand was prepared according to our previous published procedure.[7a,b] The catalytic aqueous solution was prepared by mixing equal molar amounts of **L** and $PdCl_2(NH_3)_2$ in water at room temperature and was stored in air. All ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ or d_6-DMSO at 25 °C on a Bruker 300 or 400 NMR spectrometer.

Typical procedure for the hydroxycarbonylation of aryl iodides. In a fume hood, to a 25 mL stainless autoclave equipped

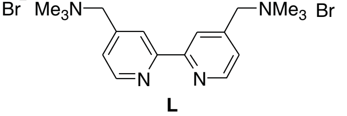

Fig. 1. Cationic 2,2′-bipyridyl ligand (**L**).

Special Issue Dedicated to Prof. Yu Wang in Honor of Her 70th Birthday

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with a magnetic stirrer bar was added aryl iodide (1.0 mmol), Na_2CO_3 (1.2 mmol), and H_2O (3 mL). After the addition of $PdCl_2(NH_3)_2$/**L** aqueous solution (1 mL; 1 × 10^{-3} mmol in 1 mL H_2O for Tables 1 and 2 and 1 × 10^{-4} mmol in 1 mL H_2O for Table 3), the reaction mixture was pressurized with CO (10 atm). The reaction vessel was then placed in an oil bath at 100 °C for 9 h (for Tables 1 and 2) or 24 h (for Table 3). After cooling of the reaction mixture to room temperature, CO gas was released in the fume hood and the aqueous solution was transferred to a test tube. This aqueous solution was added to 3 N HCl aqueous solution (2 mL) and then extracted with EtOAc (3 × 5 mL), the combined organic phase was dried over $MgSO_4$, and the solvent was then removed under vacuum. Column chromatography on silica gel afforded the desired product. All known hydroxycarbonylation products obtained were pure, and their spectra (^1H, and ^{13}C NMR) were in agreement with authentic samples.

Typical procedure for the reuse of the catalytic aqueous solution. The reaction was conducted following the procedure described previously under the reaction conditions shown in Table 2. After transferring the resulting aqueous solution to a test tube, it was extracted with EtOAc (3 × 5 mL). The combined organic phase was washed with 3 N HCl aqueous solution and then dried over $MgSO_4$. The pure product was isolated by column chromatography. The residual aqueous solution was then transferred to the stainless autoclave and charged with **1c**, Na_2CO_3, and CO for the next reaction.

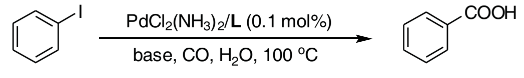
Benzoic acid (2a)[8]. ^1H NMR ($CDCl_3$, 300 MHz) δ 7.44-7.49 (m, 2H), 7.58–7.63 (m, 1H), 8.11 (d, J = 8.1 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 128.5, 129.3, 130.2, 133.9, 172.2. **4-Methylbenzoic acid (2b)[8].** ^1H NMR ($CDCl_3$, 300 MHz) δ 2.45 (s, 3H), 7.30 (d, J = 8.0 Hz, 2H), 8.03 (d, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.8, 126.6, 129.2, 130.3, 144.7, 172.6. **4-Methoxybenzoic acid (2c)[8].** ^1H NMR ($CDCl_3$, 400 MHz) δ 3.88 (s, 3H), 6.95 (d, J = 9.0 Hz, 2H), 8.07 (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 55.5, 113.8, 121.6, 132.4, 164.0, 171.5. **4-Hydroxybenzoic acid (2d)[5].** ^1H NMR (d_6-DMSO, 400 MHz) δ 6.81 (d, J = 6.4 Hz, 2H), 7.78 (d, J = 6.4 Hz, 2H), 10.17 (br, 1H); ^{13}C NMR (d_6-DMSO, 100 MHz) δ 115.6, 121.9, 132.0, 162.0, 167.6. **4-Fluobenzoic acid (2e)[9].** ^1H NMR (d_6-DMSO, 300 MHz) δ 7.11–7.24 (m, 2H), 8.10–8.14 (m, 2H); ^{13}C NMR (d_6-DMSO, 75 MHz) δ 116.1 (d, J = 21.8 Hz), 127.8, 132.6 (d, J = 9.8 Hz), 163.7, 166.9 (d, J = 13.5 Hz). **4-Chlorobenzoic acid (2f)[8].** ^1H NMR (d_6-DMSO, 400 MHz) δ 7.56 (d, J = 8.6 Hz, 2H), 7.94 (d, J = 8.6 Hz, 2H); ^{13}C NMR (d_6-DMSO, 100 MHz) δ 134.0, 134.9, 136.4, 143.0, 171.7. **4-Nitrobenzoic acid (2g)[9].** ^1H NMR (d_6-DMSO, 300 MHz) δ 8.16 (d, J = 8.7 Hz, 2H), 8.32 (d, J = 8.7 Hz, 2H); ^{13}C NMR (d_6-DMSO, 75 MHz) δ 124.2, 131.2, 136.8, 150.5, 166.2. **2-Toluic acid (2h)[8].** ^1H NMR ($CDCl_3$, 400 MHz) δ 2.65 (s, 3H), 7.25–7.29 (m, 2H), 7.42–7.46 (m, 1H), 8.05–8.07 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 22.1, 125.9, 128.4, 131.6, 131.9, 132.9, 141.4, 173.1. **2-Methoxybenzoic acid (2i)[10].** ^1H NMR ($CDCl_3$, 300 MHz) δ 4.05 (s, 3H), 7.03–7.13 (m, 2H), 7.52–7.58 (m, 1H), 8.14 (d, J = 7.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 56.8, 111.8, 117.7, 122.3, 133.6, 135.3, 158.2, 165.8. **3-Toluic acid (2j)[11].** ^1H NMR ($CDCl_3$, 300 MHz) δ 2.41 (s, 3H), 7.32–7.43 (m, 2H), 7.90–7.93 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.3, 127.4, 128.4, 129.2, 130.7, 134.6, 138.3, 172.6. **3-Methoxybenzoic acid (2k)[11].** ^1H NMR ($CDCl_3$, 300 MHz) δ 3.85 (s, 3H), 7.13–7.17 (m, 1H), 7.37 (t, J = 8.1 Hz, 1H), 7.61 (d, J = 1.2 Hz, 1H), 7.70–7.73 (m, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 55.5, 114.4, 120.5, 122.7, 129.6, 130.6, 159.6, 172.3. **3,5-Dimethylbenzoic acid (2l)[11].** ^1H NMR ($CDCl_3$, 300 MHz) δ 2.37 (s, 6H), 7.23 (s, 1H), 7.72 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.2, 127.9, 129.1, 135.5, 138.2, 172.7. **1-Naphthoic acid (2m)[11].** ^1H NMR ($CDCl_3$, 300 MHz) δ 7.52–7.58 (m, 2H), 7.63–7.68 (m, 1H), 7.91 (d, J = 7.8 Hz, 1H), 8.09 (d, J = 8.1 Hz, 1H), 8.41 (d, J = 7.5 Hz, 1H), 9.09 (d, J = 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 124.6, 125.6, 125.9, 126.4, 128.2, 128.8, 131.7, 131.9, 133.9, 134.7, 173.1.

RESULTS AND DISCUSSION

We initiated our investigation by examining the effects of bases in the hydroxycarbonylation of aryl iodides, and the influences of reaction temperature and CO pressure on the reaction were not investigated. As shown in Table 1, hydroxycarbonylation of iodobenzene **1a** catalyzed by 0.1 mol% of $PdCl_2(NH_3)_2$/**L** in the presence of 1.2 equiv Bu_3N and CO (10 atm) in water at 100 °C for 6 h led to no formation of benzoic acid **2a** (Entry 1). Hence, Bu_3N was replaced by several inorganic bases to improve the reaction. Among the inorganic bases screened, **2a** was delivered in yields between 21% and 76% (Entries 2–6), and Na_2CO_3 was found to be the best base (Entry 6). We further prolonged the reaction time to 9 h using Na_2CO_3 as the base, which furnished **2a** in a 93% isolated yield (Entry 7). The presence of the cationic 2,2′-bipyridyl ligand is critical in this Pd-catalyzed hydroxycarbonylation reaction, as only 5% of **2a** was obtained in the absence of this ligand (Entry 8). Unfortunately, this catalytic system could not catalyze hydroxycarbonylation of bromobenzene, even when activated 4-bromoacetophenone was employed (Entries 9 and 10).

After the best base for hydroxycarbonylation of aryl iodides was identified, the reusability of the aqueous cata-

Table 1. Base effects in the hydroxycarbonylation of iodobenzene **(1a)** catalyzed by $PdCl_2(NH_3)_2$/**L** in water[a]



1a **2a**

Entry	Base	Time (h)	Yield (%)[b]
1	Bu_3N	6	0
2	KOH	6	21
3	$K_3PO_4 \cdot H_2O$	6	41
4	$NaHCO_3$	6	52
5	K_2CO_3	6	45
6	Na_2CO_3	6	76
7	Na_2CO_3	9	93
8	Na_2CO_3	9	5
9[c]	Na_2CO_3	9	0
10[d]	Na_2CO_3	9	0

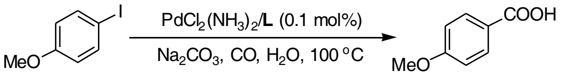
[a] Reaction conditions: **1a** (1 mmol), $PdCl_2(NH_3)_2$/**L** (0.1 mol%), base (1.2 mmol), CO (10 atm), and H_2O (4 mL) at 100 °C.

[b] Isolated yields.

[c] Bromobenzene was used instead of **1a**.

[d] 4-Bromoacetophenone was used instead of **1a**.

Table 2. Reuse studies of $PdCl_2(NH_3)_2$/**L**-catalyzed hydroxycarbonylation of 4-iodoanisole **(1c)** in water[a]



1c **2c**

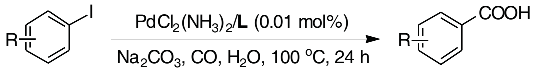
Run	Yield (%)[b]	TON	Run	Yield (%)[b]	TON
1	93	930	6	79	790
2	88	880	7	74	740
3	85	850	8	76	760
4	82	820	9	56	560
5	80	800	Overall	713	7130

[a] Reaction conditions: **1c** (1 mmol), $PdCl_2(NH_3)_2$/**L** (0.1 mol%), Na_2CO_3 (1.2 mmol), CO (10 atm), and H_2O (4 mL) at 100 °C for 9 h.

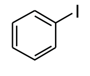
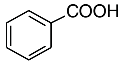
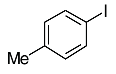
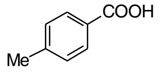
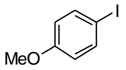
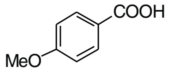
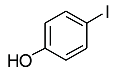
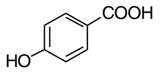
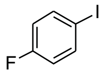
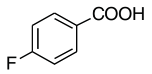
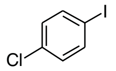
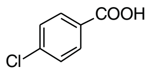
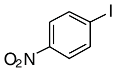
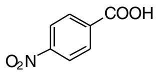
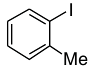
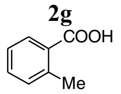
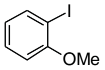
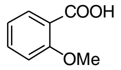
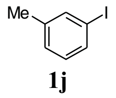
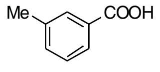
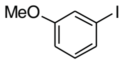
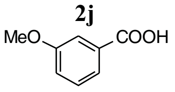
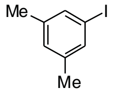
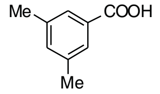
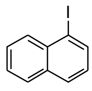
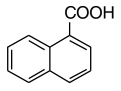
[b] Isolated yields.

lytic system was then evaluated. 4-Iodoanisole **1c** was used as the reactant under the reaction conditions shown in Table 1, Entry 7. As illustrated in Table 2, after extraction of the reaction mixture with EtOAc at the end stage of the initial run (Run 1), the residual aqueous solution was able to be reused for the same reaction at least 8 times with only a slight decrease in activity in each reuse run. It gave overall yields of 713%, corresponding to turnover numbers (TON) of 7130 and an average yield of 79% for each reuse run. In comparison with hydroxycarbonylation of iodobenzene in

Table 3. $PdCl_2(NH_3)_2$/**L**-catalyzed hydroxycarbonylation of aryl iodides in water[a]



1 **2**

Entry	Aryl iodide	Product	Yield (%)[b]	TON
1	 **1a**	 **2a**	99	9900
2	 **1b**	 **2b**	82	8200
3	 **1c**	 **2c**	93	9300
4[c]	 **1d**	 **2d**	83	8300
5	 **1e**	 **2e**	74	7400
6	 **1f**	 **2f**	65	6500
7	 **1g**	 **2g**	76	7600
8	 **1h**	 **2h**	71	7100
9	 **1i**	 **2i**	82	8200
10	 **1j**	 **2j**	86	8600
11	 **1k**	 **2k**	76	7600
12	 **1l**	 **2l**	85	8500
13	 **1m**	 **2m**	90	9000

[a] Reaction conditions: **1** (1 mmol), $PdCl_2(NH_3)_2$/**L** (0.01 mol%), Na_2CO_3 (1.2 mmol), CO (10 atm), and H_2O (4 mL) at 100 °C for 24 h.

[b] Isolated yields.

[c] Na_2CO_3 (2.2 mmol) was used.

ionic liquid under an identical catalyst loading,[6] our catalytic system showed excellent stability during the reuse experiments. The slow gradual decrease in the product yield in each reuse run may be mainly due to the loss of catalyst concentration upon successive extraction with EtOAc and transfer of the aqueous catalytic solution between autoclave and test tube in each reuse run. However, the possibility of gradual deactivation of the catalyst during each reuse run may not be excluded.

The results of the reuse studies encouraged us to further reduce the catalyst loading to 0.01 mol%. To our delight, under the reaction conditions shown in Table 3, **1a** was transformed to **2a** completely in 24 h, providing an isolated yield of 99%, corresponding to a TON of 9900 (Entry 1). When various *para*-substituted aryl iodides were employed, with not only electron-rich **1b–1d**, but also electron-deficient aryl iodides, **1e–1g**, a range of 65%–93% product yields were achieved (Entries 2–7). Even when sterically-hindered *ortho*-substituted aryl iodides, **1h** and **1i**, were employed, 71% and 82% yields were obtained, respectively (Entries 8 and 9). With regards to *meta*-substituted aryl iodides and 1-iodonaphthalene, **1j–1m**, the hydroxycarbonylation reaction took place smoothly, resulting in the formation of corresponding aromatic carboxylic acids **2j–2m** in yields between 76% and 90% (Entries 10–13).

CONCLUSIONS

We have shown here that hydroxycarbonylation of aryl iodides catalyzed by a water-soluble $PdCl_2(NH_3)_2$/cationic 2,2′-bipyridyl catalytic system gives aromatic carboxylic acids in high yields at a very low catalyst loading level (0.01 mol%). This water-compatible catalytic system enables easy separation from the organic product by simple extraction, and the residual aqueous solution can be reused for further reactions, which reduces wastage of the precious metal.

ACKNOWLEDGEMENTS

The research was financially supported by the National Science Council of Taiwan (NSC98-2113-M-027-001-MY3).

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