

Sulfonamide- and hydrazine-based palladium catalysts: Stable and efficient catalysts for C–C coupling reactions in aqueous medium

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Abstract

Syntheses of a novel family of sulfonamide-based palladium complexes and phenylhydrazine-based palladacycles are described. These catalysts are thermally stable, and not sensitive to air and moisture and some are completely soluble in water. These catalysts have shown excellent activity (good yields and high turnover numbers) and product selectivity in several arylation reactions including Suzuki, Heck, and Sonogashira reactions carried out totally under aqueous conditions.

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Keywords: Suzuki coupling reaction; Heck reaction; Sonogashira reaction; Arylation reaction; Palladium catalyst

1. Introduction

Palladacycles have recently emerged as one of the most promising classes of catalysts or catalyst precursors in the Pd-catalyzed C–C bond forming reactions such as Heck–Mizoroki [1], Suzuki–Miyaura [2], and Sonogashira reactions [3]. In the last decade, a number of new types of ligands such as heterocyclic carbenes [4], thiourea [5], oxime palladacycles [6], diazabutadienes [7] and 2-aryl-2-oxazolines [8] were employed in these cross-coupling reactions. However, a high loading of catalysts and an inert atmosphere in most reactions especially involving phosphapalladacycles [9] and phosphines-free *N*-heterocyclic carbenes are generally required for achieving better conversions. Thus, the search for new palladium catalysts has received much attention particularly for the use of less reactive aryl chlorides as substrates, under aerobic conditions or even in aqueous solutions. Aqueous-phase palladium catalyzed reactions are of much interest as environmentally benign synthetic methods that would avoid the use of volatile organic solvents and simplify the catalyst recovery. Although there are a few reports available on Pd catalysts with water-soluble sulfonated phosphine [10] ligands, to the best of our

knowledge, no information is available on completely soluble Pd-catalysts. We reported our earlier results on highly active cyclopalladated sulfilimine-derived palladacycles for a wide range of useful and well-known C–C coupling reactions [11].

In the continuation of our interest in the development of new ligands for Pd-catalyzed C–C bond forming reactions, we report here the synthesis of several novel sulfonamide Pd complexes (1–5) as well as phenylhydrazine-derived palladacycles (6–9) (Fig. 1) and their catalytic performance in several C–C bond forming cross-coupling reactions in water as the solvent.

2. Experimental

2.1. Materials and methods

Solvents were purified and dried by standard procedures before use; petroleum ether of boiling range 60–80 °C was used. Melting points are uncorrected. Infrared spectra were recorded on a Shimadzu FTIR-8400 spectrometer. ¹H NMR and ¹³C NMR were recorded on a Bruker AC-200 spectrometer. Mass spectra were obtained with a Finnigan MAT-1020 B-70 eV mass spectrometer. Elemental analysis was carried out on a Carlo Erba CHNS-O analyzer. The TEM analysis was carried out on a JEOL 2010 transmission electron microscope operating at 100 kV at magnifications varying from 100 to 300 K.

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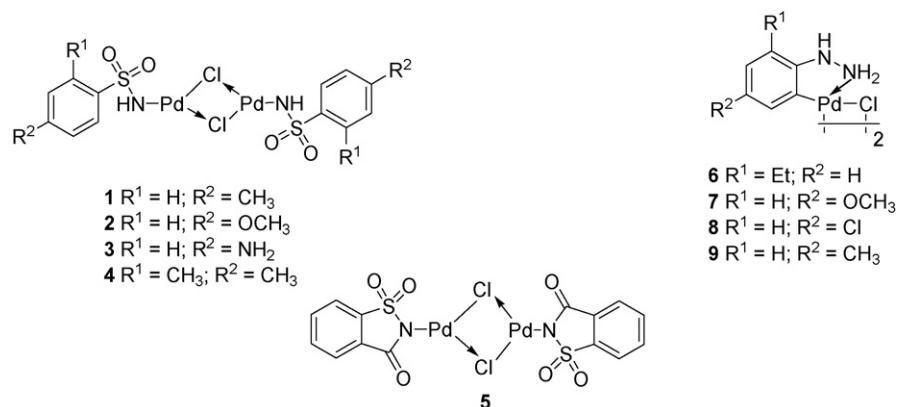


Fig. 1. Sulfonamide-based palladium complexes (1–5) and phenylhydrazine-based palladacycles (6–9).

2.2. Preparation of palladium complexes 1–4 [12]

A two-necked 25 mL RB flask was charged with PdCl₂ (177 mg, 1 mmol), LiCl (100 mg, 2.4 mmol) and MeOH (2 mL); the resulting reaction mixture was stirred under argon atmosphere at 25 °C for 2.5 h. Then to this reaction mixture were added NaOAc (123 mg, 1.5 mmol), and a solution of 4-methylsulfonamide (171 mg, 1 mmol) in MeOH (2 mL). The resulting reaction mixture was stirred at 25 °C for 24 h. Then, distilled water (6 mL) was added to it and the resulting solid was filtered on a sintered funnel, washed with water and dried under reduced pressure (5 mm of Hg) for 3 h to afford palladium complexes **1** as yellow coloured solid (256 mg, 82%).

2.2.1. Characterization of palladium complex

2.2.1.1. Palladium complex 1. Pale-yellow solid, yield: (256 mg, 82%) mp: 195–198 °C (dec.); IR (KBr, cm⁻¹) $\nu = 559, 721, 813, 1083, 1157, 1305, 1340, 1377, 1463, 1521, 2358, 2675, 2727, 2852, 2916$ cm⁻¹; ¹H NMR (200 MHz, DMSO-*d*₆): δ 2.19 (s, 3H, CH₃), 7.11–7.19 (m, 2H, ArH), 7.54–7.55 (m, 2H, ArH); ¹³C NMR (50 MHz, DMSO-*d*₆): δ 21.17 (CH₃); 125.48, 129.57, 141.55, 142.19 (ArC); elemental analysis calculated for C₁₄H₁₆Cl₂N₂O₄Pd₂S₂: C, 26.94; H, 2.58; Cl, 11.36; N, 4.49; S, 10.28. Found: C, 26.88; H, 2.45; Cl, 11.54; N, 4.55; S, 10.19%.

2.2.1.2. Palladium complex 2. Pale-yellow solid, yield: (256 mg, 78%) mp: 198–201 °C (dec.); IR (KBr, cm⁻¹) $\nu = 561, 680, 721, 804, 1022, 1085, 1153, 1261, 1301, 1375, 1456, 1538, 1652, 1683, 2673, 2852, 2923$; ¹H NMR (200 MHz, DMSO-*d*₆): δ 3.75 (s, 3H, OCH₃), 7.01–7.12 (m, 2H, ArH), 7.79–7.82 (m, 2H, ArH); ¹³C NMR (50 MHz, DMSO-*d*₆): δ 55.97 (OCH₃), 114.40, 128.07, 136.27, 162.05 (ArC); elemental analysis calculated for C₁₄H₁₆Cl₂N₂O₆Pd₂S₂: C, 25.63; H, 2.46; Cl, 10.81; N, 4.27; S, 9.76. Found: C, 26.75; H, 2.35; Cl, 10.97; N, 4.23; S, 9.87%.

2.2.1.3. Palladium complex 3. Pale-yellow solid, yield: (238 mg, 76%) mp: 305–308 °C (dec.); IR (KBr, cm⁻¹) $\nu = 559, 678, 721, 891, 1087, 1151, 1313, 1375, 1456, 1506, 1558, 1652,$

1683, 1733, 2671, 2854, 2923; ¹H NMR (200 MHz, DMSO-*d*₆): δ 6.72–6.84 (m, 2H, ArH), 7.63–7.78 (m, 2H, ArH); ¹³C NMR (50 MHz, DMSO-*d*₆): δ 112.99, 127.86, 130.35, 152.31 (ArC); elemental analysis calculated for C₁₂H₁₄Cl₂N₄O₄Pd₂S₂: C, 23.02; H, 2.25; Cl, 11.32; N, 8.95; S, 10.25. Found: C, 23.25; H, 2.17; Cl, 11.21; N, 8.74; S, 10.44%.

2.2.1.4. Palladium complex 4. Pale-yellow solid, yield: (235 mg, 72%) mp: 220–223 °C (dec.); IR (KBr, cm⁻¹) $\nu = 721, 1130, 1149, 1168, 1317, 1340, 1377, 1456, 1463, 1558, 1652, 1683, 2852, 2923, 2954$; ¹H NMR (200 MHz, acetone-*d*₆): δ 2.25 (s, 3H, CH₃), 2.58 (s, 3H, CH₃), 6.59–7.76 (m, 3H, ArH); ¹³C NMR (50 MHz, acetone-*d*₆): δ 20.03 (CH₃), 20.95 (CH₃), 127.04, 128.24, 133.45, 136.87, 139.71, 143.16 (ArC); elemental analysis calculated for C₁₆H₂₀Cl₂N₂O₄Pd₂S₂: C, 29.46; H, 3.09; Cl, 10.87; N, 4.30; S, 9.84. Found: C, 29.66; H, 2.98; Cl, 10.74; N, 4.45; S, 9.72%.

2.3. Preparation of palladium complex 5

A two-necked 25 mL RB flask was charged with PdCl₂ (177 mg, 1 mmol), LiCl (100 mg, 2.4 mmol) and MeOH (2 mL); the resulting reaction mixture was stirred under argon atmosphere at 25 °C for 2.5 h. Then to this reaction mixture were added NaOAc (123 mg, 1.5 mmol), and a solution of saccharin (183 mg, 1 mmol) in MeOH (2 mL). The resulting reaction mixture was stirred at 25 °C for 6 h. Then, the resulting solid was filtered on a sintered funnel, dried under reduced pressure (5 mm of Hg) for 3 h to afford palladium complex **5** as yellow coloured solid (275 mg, 85%).

2.3.1. Characterization of palladium complex 5

Pale-yellow solid, yield: (275 mg, 85%) mp: 237–240 °C (dec.); IR (KBr, cm⁻¹) $\nu = 594, 756, 984, 1154, 1287, 1287, 1456, 1664, 1951, 3590$; ¹H NMR (200 MHz, DMSO-*d*₆): δ 7.21–7.34 (m, 4H, ArH); ¹³C NMR (50 MHz, DMSO-*d*₆): δ 119.74, 123.19, 131.95, 133.37, 134.65, 145.29, 169.02 (ArC); elemental analysis calculated for C₁₄H₈Cl₂N₂O₆Pd₂S₂: C, 25.95; H, 1.24; Cl, 10.94; N, 4.32; S, 9.9. Found: C, 25.87; H, 1.40; Cl, 11.05; N, 4.15; S, 9.78%.

2.4. Preparation of palladacycles (6–9)

A two-necked 25 mL RB flask was charged with PdCl₂ (177 mg, 1 mmol), LiCl (100 mg, 2.4 mmol) and MeOH (2 mL); the resulting reaction mixture was refluxed under argon atmosphere for 2.5 h. Then to this reaction mixture was added a solution of 2-ethylphenylhydrazine (136 mg, 1 mmol) in MeOH (2 mL). The resulting reaction mixture was refluxed for 3 h. Then, the resulting solid was filtered on a sintered funnel, dried under reduced pressure for 3 h to afford palladacycles **6** as yellow coloured solid (186 mg, 67%).

2.4.1. Characterization of palladium complex

2.4.1.1. Palladacycle 6. Brown solid, yield: (186 mg, 67%) mp: 310–312 °C (dec.); IR (KBr, cm⁻¹) ν = 769, 1215, 1490, 2399, 3018, 3301; ¹H NMR (200 MHz, CDCl₃) δ 1.27–1.19 (t, J = 8.0 Hz, 3H, CH₃), 2.62–2.47 (q, J = 8.0 Hz, 2H, CH₂), 7.13–6.96 (m, 3H, ArH); ¹³C NMR (50 MHz, CDCl₃) δ 12.92 (CH₃), 23.35 (CH₂), 121.90, 125.99, 127.43, 127.79, 127.89, 136.21 (ArC); elemental analysis calculated for C₈H₁₁N₂PdCl: C, 34.68; H, 4.00; N, 10.11; Cl, 12.80. Found: C, 34.68; H, 4.06; N, 10.15; Cl, 12.76%.

2.4.1.2. Palladacycle 7. Brown solid, yield: (190 mg, 68%) mp: 291–294 °C (dec.); IR (KBr, cm⁻¹); ν = 433, 769, 1217, 1238, 1504, 2352, 3232; ¹H NMR (200 MHz, CDCl₃) δ 4.03 (s, 1H, OCH₃), 5.85 (bs, 2H, NH₂), 6.85 (d, J = 8.9 Hz, 1H, ArH), 7.70 (s, 1H, ArH), 7.82 (d, J = 8.9 Hz, 1H, ArH); ¹³C NMR (50 MHz, CDCl₃) δ 54.50 (OCH₃), 122.50, 125.17, 127.23, 127.84, 135.84, 144.05 (ArC); elemental analysis calculated for C₇H₉N₂OPdCl: C, 30.13; H, 3.25; N, 10.04; Cl, 12.71. Found: C, 30.08; H, 3.27; N, 10.07; Cl, 12.75%.

2.4.1.3. Palladacycle 8. Brown solid, yield: (187 mg, 66%); mp: 308–311 °C (dec.); IR (KBr, cm⁻¹); ν = 741, 836, 925, 1060, 1126, 1287, 1418, 1508, 1606, 1818, 2565, 2760, 2858, 3772; ¹H NMR (200 MHz, CDCl₃) δ 7.95 (d, J = 9.9 Hz, 1H, ArH), 8.35 (d, J = 9.9 Hz, 1H, ArH), 8.97 (s, 1H, ArH); ¹³C NMR (50 MHz, CDCl₃) δ 116.35, 117.95, 129.02, 129.17, 129.64, 141.73 (ArC); elemental analysis calculated for C₆H₆N₂PdCl₂: C, 25.42; H, 2.13; N, 9.88; Cl, 25.02. Found: C, 25.45; H, 2.18; N, 9.89; Cl, 25.08%.

2.4.1.4. Palladacycle 9. Brown solid, yield: (168 mg, 64%) mp: 336–340 °C (dec.); IR (KBr, cm⁻¹); ν = 653, 910, 1030, 1197, 1244, 1350, 1514, 1633, 1866, 2061, 2279, 2472, 3001, 3234; ¹H NMR (200 MHz, CDCl₃) δ 2.22 (s, 1H, CH₃), 6.92 (s, 1H, ArH), 7.12 (d, J = 8.1 Hz, 1H, ArH), 7.39 (d, J = 8.1 Hz, 1H, ArH); ¹³C NMR (50 MHz, CDCl₃) δ 24.90 (CH₃), 120.99, 124.21, 125.09, 126.35, 127.04, 136.49 (ArC); elemental analysis calculated for C₇H₉N₂PdCl: C, 31.96; H, 3.45; N, 10.65; Cl, 13.48. Found: C, 31.98; H, 3.47; N, 10.63; Cl, 13.45%.

2.5. General experimental procedure for the Heck reaction

A two-necked 25 mL RB flask with double walled water condenser was charged with 4-bromoanisole (374 mg, 2.0 mmol),

K₂CO₃ (552 mg, 4.0 mmol), styrene (312 mg, 3.0 mmol), water (6 mL) and tetrabutylammonium bromide (644 mg, 2 mmol). To this mixture palladium complex **5** (0.00324 mg, 5×10^{-6} mmol) was added. The reaction mixture was then heated in an oil bath at specified temperature and time (Table 2). The progress of the reaction was monitored by TLC. The reaction mixture was then allowed to cool to 25 °C and extracted with ethyl acetate (3 \times 10 mL). The combined organic extracts were washed with brine and dried over anhydrous sodium sulfate and concentrated under reduced pressure to afford the crude product. The crude product was then purified by column chromatography on silica gel using petroleum ether and ethyl acetate as eluents to afford the 1-(4-methoxyphenyl)-2-phenylethylene as a colourless solid (391 mg, 93%).

2.6. General procedure for the Suzuki coupling

A two-necked 25 mL RB flask was charged with 4-bromoanisole (935 mg, 5.0 mmol), phenylboronic acid (915 mg, 7.5 mmol), KOH (560 mg, 10 mmol), palladium complex **5** (0.032 mg, 5×10^{-5} mmol), tetrabutylammonium bromide (1610 mg, 5 mmol) and water (15 mL). The reaction mixture was stirred at 25 °C at specified time (Table 3) (the progress of the reaction was monitored by TLC). After the specified time, the product was isolated by extraction with dichloromethane (3 \times 25 mL). The combined organic extracts were washed with brine and dried over anhydrous sodium sulfate and concentrated under reduced pressure to afford the crude product. The crude product was then purified by column chromatography on silica gel using petroleum ether and ethyl acetate as eluent to afford 4-methoxybiphenyl as a colourless solid (746 mg, 81%).

2.6.1. Reuse of catalysts for the Suzuki coupling of 4-bromotoluene with phenylboronic acid

A two-necked 25 mL RB flask was charged with 4-bromotoluene (855 mg, 5.0 mmol), phenylboronic acid (915 mg, 7.5 mmol), KOH (560 mg, 10 mmol), palladium complex **5** (0.032 mg, 5×10^{-5} mmol), tetrabutylammonium bromide (1610 mg, 5 mmol) and water (15 mL). The reaction mixture was stirred at 25 °C for 3 h. The product was isolated by extraction with diethyl ether (3 \times 25 mL) to yield 4-methylbiphenyl as a colourless solid (798 mg, 95%). For the second cycle, 4-bromotoluene (855 mg, 5.0 mmol), phenylboronic acid (915 mg, 7.5 mmol) were added to the aqueous layer from the first cycle containing palladium catalyst and base. The resulting reaction mixture was stirred for 3 h. Then the same workup procedure was repeated to yield 4-methylbiphenyl (798 mg, 95%). Thus, the catalyst was reused at least five times without any considerable loss of the catalytic activity.

2.7. General procedure for the Sonogashira coupling

A two-necked 25 mL RB flask was charged with iodobenzene (1020 mg, 5 mmol), phenylacetylene (765 mg, 7.5 mmol), palladium complex **5** (0.324 mg, 5×10^{-4} mmol), KOH (560 mg, 10 mmol), tetrabutylammonium bromide (1610 mg, 5 mmol) and water (15 mL). The resulting mixture was stirred at 100 °C

for 6 h. Then the reaction mixture was extracted with ethyl acetate (3×20 mL) and washed with brine, dried over anhydrous sodium sulfate and concentrated under reduced pressure. This crude product was purified on column chromatography using 10% ethyl acetate in petroleum ether as eluent to afford 1,2-diphenylethyne as a colourless solid (802 mg, 90%).

2.8. General procedure for arylation of allylic alcohol

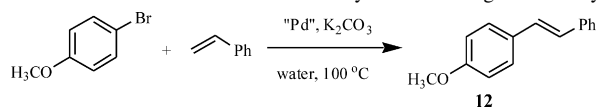
A two-necked 25 mL RB flask was charged with iodobenzene (1020 mg, 5 mmol), allyl alcohol (435 mg, 7.5 mmol), palladium complex **6** (0.277 mg, 5×10^{-4} mmol), K_2CO_3 (1380 mg, 10 mmol), tetrabutylammonium bromide (1610 mg, 5 mmol) and water (15 mL). The resulting mixture was stirred at $80^\circ C$ for 6 h. Then the reaction mixture was extracted with ethyl acetate (3×20 mL) and washed with brine, dried over anhydrous sodium sulfate and concentrated under reduced pressure. This crude product was purified on column chromatography using 5% ethyl acetate in petroleum ether as eluent to afford 3-phenylpropanal as a colourless liquid (597 mg, 89%).

3. Results and discussion

3.1. Catalytic Heck reaction

The catalytic activities of the synthesized Pd complexes were evaluated for the Heck cross-coupling reaction between 4-bromoanisole and styrene at $100^\circ C$ in the presence of K_2CO_3 as base under aqueous, ligand-free conditions and the results are presented in Table 1. It is noteworthy that among all the palladium complexes screened catalysts **5** and **6** have exhibited high activity for the Heck reaction with a turnover number (TON) of 372,000 (yield: 93%) and 364,000 (yield: 91%) respectively (entries 5 and 6). We observed that in comparison with $Pd(OAc)_2$

Table 1
Heck reaction of 4-bromoanisole with styrene: screening of Pd catalysts^a



Entry	Palladium catalyst	Yield of 12 (%) ^b	TON ^c
1	1	89	356,000
2	2	85	340,000
3	3	82	328,000
4	4	88	352,000
5	5	93	372,000
6	6	91	364,000
7	7	86	344,000
8	8	85	340,000
9	9	86	344,000
10	$Pd(OAc)_2$ ^{1e}	71	1,420
11	10 ^{1f}	78	500
12	11 ^{1g}	51	13,000

^a Reaction conditions: 4-bromoanisole (2 mmol), styrene (3 mmol), K_2CO_3 (4 mmol), palladium complex (5×10^{-6} mmol), tetrabutylammonium bromide (2 mmol), water (6 mL), 6 h.

^b Isolated yields after chromatographic purification.

^c TON = turnover number, defined as mmol of product/mmol of Pd.

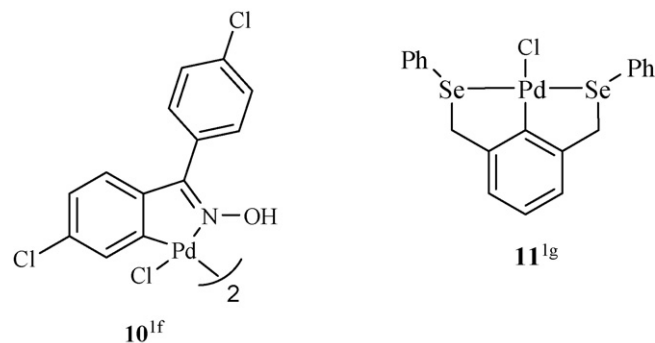


Fig. 2. Representative examples of palladacycles for Heck reactions.

and other known palladacycles (Fig. 2), catalysts **5** and **6** gave a high yield as well as high TON in the Heck reaction between 4-bromoanisole and styrene carried out in the aqueous medium. (Table 1, entries 10–12).

3.1.1. Heck reaction of aryl bromides with olefins

We have then used a wide variety of aryl bromides and olefins to Heck reaction using Pd catalysts **5** and **6** and the results are shown in Table 2. For both activated and unactivated aryl bromides excellent conversions were obtained within 6 h. However, in the case of activated aryl chlorides (entries 12 and 13) catalyst **5** gave only a moderate yield.

3.2. Catalytic Suzuki cross-coupling reactions

The catalytic activity of Pd catalysts **5** and **6** for Suzuki reaction was evaluated by taking aryl bromides and boronic acids as coupling partners. Under the optimized conditions, various acti-

Table 2
Heck reaction between aryl halides and olefinic substrates catalyzed by **5** and **6**^a

Entry	ArX	Y	Yields of 13 (%) ^b	
			Catalyst 5	Catalyst 6
1	4-Bromotoluene	CO ₂ Me	97	91
2	4-Bromotoluene	CO ₂ ⁿ Bu	94	83
3	1-Bromonaphthalene	Ph	98	95
4	1-Bromonaphthalene	CO ₂ Me	89	82
5	1-Bromonaphthalene	CO ₂ ⁿ Bu	81	80
6	3-Bromobenzotrifluoride	CO ₂ ⁿ Bu	94	86
7	3-Bromobenzotrifluoride	CO ₂ Et	95	84
8	Bromobenzene	CO ₂ ⁿ Bu	95	89
9	Bromobenzene	Ph	97	94
10	4-Bromoanisole	CO ₂ Et	85	80
11	2-Bromo-6-methoxy-naphthalene	CO ₂ ⁿ Bu	87	79
12	4-Chloronitrobenzene	CO ₂ Et	45	NR ^c
13	4-Chloronitrobenzene	CO ₂ ⁿ Bu	56	NR ^c

^a Reaction conditions: aryl halide (2 mmol), olefin (3 mmol), K_2CO_3 (4 mmol), palladium complex (5×10^{-6} mmol), tetrabutylammonium bromide (2 mmol), water (6 mL), $100^\circ C$, 6 h.

^b Isolated yields after chromatographic purification.

^c No reaction occurred.

Table 3
Suzuki coupling of aryl halides with arylboronic acids catalyzed by **5** and **6**^a

Entry	Ar'	ArX	Yields of 14 (%) ^b	
			Catalyst 5	Catalyst 6
1	Ph	4-Bromoanisole	81	78
2	Ph	2-Bromoanisole	78	72
3	Ph	4-Bromotoluene	95	83
4	Ph	Bromobenzene	96	98
5	Ph	2-Bromonaphthalene	89	82
6	Ph	3-Bromobenzotrifluoride	90	85
7	Ph	4-Chloroacetophenone ^c	78	NR ^d
8	Ph	2-Nitrochlorobenzene ^c	75	NR ^d
9	Ph	4-Toluenesulfonyl chloride	80	67
10	Ph	Benzenesulfonyl chloride	78	63
11	4-Acetyl Ph	Bromobenzene	71	70
12	4-Acetyl Ph	4-Bromoanisole	81	90
13	4-Acetyl Ph	4-Bromotoluene	79	78
14	4-Acetyl Ph	1-Bromonaphthalene	78	77
15	3-Chloro Ph	4-Nitrobromobenzene	78	73
16	3-Chloro Ph	4-Bromotoluene	70	71
17	3-Chloro Ph	1-Bromonaphthalene	69	76
18	3-Chloro Ph	Bromobenzene	86	78
19	1-Naphthyl	Bromobenzene	81	78

^a Reaction conditions: aryl halide (5 mmol), phenylboronic acid (7.5 mmol), KOH (10 mmol), palladium catalyst (5×10^{-5} mmol), tetrabutylammonium bromide (5 mmol), water (15 mL), 25 °C, 3 h.

^b Isolated yields after chromatographic purification.

^c Reaction was carried out at 100 °C.

^d No reaction occurred.

vated and unactivated aryl bromides underwent coupling with a wide range of phenylboronic acids in water as the solvent (Table 3). Among the bases (K_2CO_3 , KO^tBu , KOH and CS_2CO_3) screened, KOH gave the best yield.

It is remarkable that good yields of biaryls were obtained for the aryl chlorides having electron-withdrawing groups like acyl, nitro (entries 6 and 7). For the coupling of 4-chloroacetophenone with phenylboronic acid, a good yield of 78% was achieved with a TON of 78,000. Pd catalyst **5** is readily soluble in water under ambient conditions, which makes its separation easier from the biaryls formed.

The results of the reusability study of the palladium complex **5** for the Suzuki coupling of 4-bromotoluene with phenylboronic acid for the five cycles is presented in Table 4. As can be seen, there is only marginal decrease in the yield of the biphenyl (88%) for the fifth cycle as compared to the yield obtained for the first cycle (95%).

3.3. Catalytic Sonogashira reactions

Sonogashira reactions utilize palladium salts in catalytic amounts along with other metal as a co-catalyst and a base. Typically, copper is used as a co-catalyst but suffers from the homocoupling of the expensive alkynes. Copper-free Sonogashira reactions have also been reported [13]. We evaluated the effectiveness of Pd catalyst **5** for Sonogashira coupling reactions under totally copper-free conditions using water in the presence

Table 4
Reusability study of the palladium complex **5** for the Suzuki coupling of 4-bromotoluene with phenylboronic acid^a

Entry	Reaction cycle	Yield (%) ^b
1	1	95
2	2	95
3	3	93
4	4	90
5	5	88

^a Reaction conditions: aryl halide (5 mmol), phenylboronic acid (7.5 mmol), KOH (10 mmol), palladium catalyst (5×10^{-5} mmol), tetrabutylammonium bromide (5 mmol), water (15 mL), 25 °C, 3 h.

^b Isolated yields after chromatographic purification.

of KOH (Table 5). Excellent yields of acetylenic compounds (**15**) were obtained for the aryl iodides, although the Pd catalysts have shown only the moderate activity for aryl bromides as well as chlorides.

3.4. Catalytic arylation of allylic alcohols

Arylation of allylic alcohols [14] constitutes a powerful method in organic synthesis for the generation of a three-carbon unit with an aldehydic group. We have carried out arylation of allylic alcohols with aryl halides either with K_2CO_3 or diisopropylamine as base using phenylhydrazine-based palladacycles (**6–9**) as catalysts in water at 80 °C. The novel feature of our system is the selective formation of either α,β -unsaturated alcohols or saturated carbonyl compounds. Selective formation of aromatic conjugated alcohols was observed in the case of aryl halides with electron-withdrawing groups whereas saturated aldehydes were formed when aryl halides with electron-donating groups were used. Good yields of ketones were obtained when secondary allylic alcohol was subjected to arylation reaction (entry 4; Table 6). This selectivity can be explained by the fact that the β hydride elimination from the carbopalladation intermediate **16** can take place from both the available β -hydrogens. Electron-withdrawing group on the aromatic ring makes the


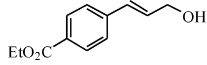
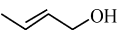
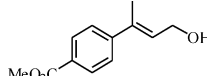

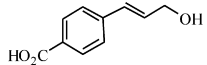
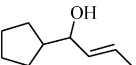
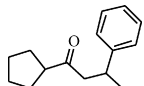

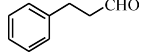
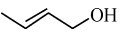
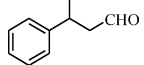

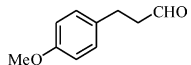
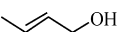
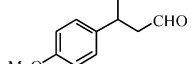

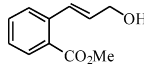

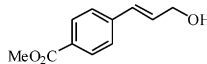
Table 5
Sonogashira coupling catalyzed water-soluble saccharin palladium complex **5**^a

Entry	Aryl halides (Ar-X)	Alkynes (R)	Yield of 15 (%) ^b
1	C_6H_5I	C_6H_5	90
2	$4-O_2NC_6H_4I$	C_6H_5	93
3	C_6H_5Br	C_6H_5	70
4	C_6H_5Br	4-Me C_6H_4	66
5	$4-O_2NC_6H_4Br$	C_6H_5	72
6	4-Me C_6H_4Br	C_6H_5	57
7	C_6H_5Cl	C_6H_5	20

^a Reaction conditions: aryl halide (5 mmol), alkyne (7.5 mmol), KOH (10 mmol), tetrabutylammonium bromide (5 mmol), water (15 mL), palladium complex **5** (5×10^{-4} mmol), 100 °C, 6 h.

^b Isolated yields after chromatographic purification.

Table 6
Arylation of aryl halides with (Ar-X) allylic alcohols catalyzed by palladacycle **6**^a

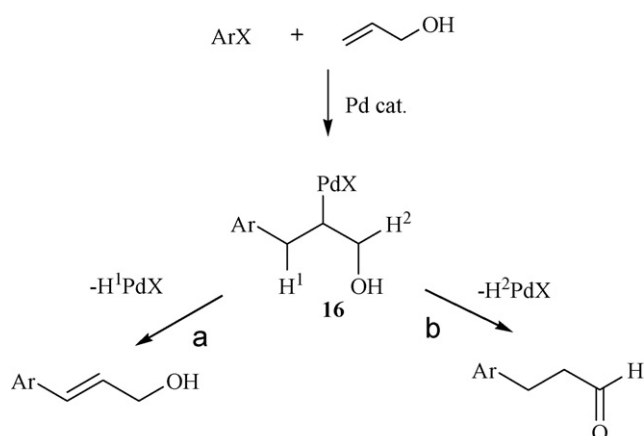
Entry	Ar-X	Alcohol	Base	Product	Yield (%) ^b
1	Ethyl 4-bromobenzoate		DIPA ^c		82
2	Methyl 4-bromobenzoate		DIPA		88
3	4-Bromobenzoic acid		K ₂ CO ₃		71
4	Iodobenzene		K ₂ CO ₃		63
5	Iodobenzene		K ₂ CO ₃		89
6	Iodobenzene		K ₂ CO ₃		73
7	4-Iodoanisole		K ₂ CO ₃		73
8	4-Iodoanisole		DIPA		92
9	Methyl 2-iodobenzoate		DIPA		90
10	Methyl 4-iodobenzoate		DIPA		81

^a Reaction conditions: aryl halide (5 mmol), allyl alcohol (7.5 mmol), base (10 mmol), tetrabutylammonium bromide (5 mmol), water (15 mL), catalyst **6** (5×10^{-4} mmol), 80 °C, 12 h.

^b Isolated yields after chromatographic purification.

H¹-β hydrogen more acidic, thus facilitating its removal as palladium hydride species resulting in the formation of aromatic conjugated alcohols (route a) while formation of aldehydes takes place by the elimination of H²-β hydrogen [15] (Scheme 1).

The formation of Pd(0) nanoparticles was investigated by subjecting the reaction mixture consisting of iodobenzene, allyl alcohol and palladacycle **6** in water after 12 h to “*in situ*”



Scheme 1. Plausible mechanism for arylation with allylic alcohols.

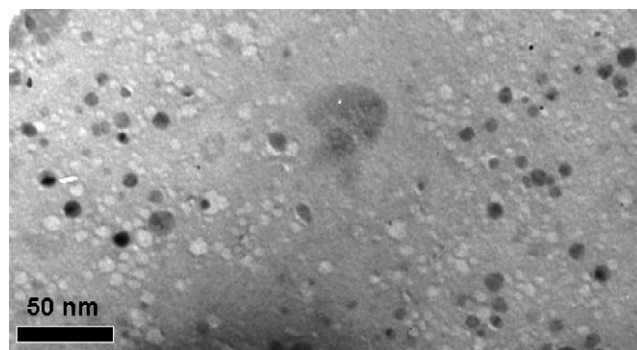


Fig. 3. TEM image of Pd nanoparticles formed after 12 h for the reaction between iodobenzene and allyl alcohol using palladacycle **6** in the aqueous medium.

TEM analysis. The TEM measurement for the aqueous medium (Fig. 3) confirms the presence of Pd(0) nanoparticles of spherical morphology varying in diameter from 10 to 12 nm.

4. Conclusion

In summary, a novel family of sulfonamide-based palladium complexes and phenylhydrazine-based palladacycles from

inexpensive and readily available ligands have been synthesized. These novel Pd catalysts are air, moisture-stable and some are completely soluble in water (Pd catalyst **5**), which were used for C–C bond forming reactions like Suzuki, Heck, Sonogashira reactions and arylation of allyl alcohols. High TON (often reaching up to 372,000), totally phosphine-free conditions and reactions in aqueous media are some of the salient features of the study. The TEM analysis confirms the *in situ* formation of palladium(0) nanoparticles (size 10–12 nm) in the case of palladacycle. The palladium catalyst was reused several times without significant loss of catalytic activity.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2006.12.023.

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