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Synthesis and catalytic activity of pyrazolyl-functionalized *N*-heterocyclic carbene palladium complexes

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Abstract Three pyrazolyl-functionalized *N*-heterocyclic carbene (NHC) palladium complexes based on 1-[2-(pyrazol-1-yl)phenyl]imidazole have been synthesized and characterized by physico-chemical and spectroscopic methods, and the structures of two of the complexes have been confirmed by single-crystal X-ray diffraction. The pyrazolyl-functionalized NHCs act as chelating N,C-bidentate ligands in these three complexes. Catalytic tests have proved that these complexes exhibit highly effective catalytic activity for the Suzuki–Miyaura and Mizoroki–Heck coupling reactions in water or aqueous/organic media under air. The substituents on the pyrazolyl ring exert different influences on the catalytic activity of the complexes in these coupling reactions.

Introduction

N-Heterocyclic carbenes (NHCs) and their transition metal complexes have become ubiquitous in coordination and organometallic chemistry [1–4], since the isolation of the first isolable NHC [5]. Recent investigations demonstrated that NHCs with additional donor functionalities can provide relatively stable and efficient catalysts or catalyst precursors through the reversible coordination/dissociation process of the donor functions from the metal centers. Thus, various classical donor-functionalized NHC ligands, such as N-, P-, O-, and S-functionalized NHCs [6–11], have been synthesized and used in a large number of catalytic transformations. In the family of nitrogen-functionalized NHCs, pyrazolyl-functionalized NHCs [12–17] have attracted considerable attention owing to the coordination versatility of pyrazole-based ligands and the catalytic activity of their complexes [18–20]. Moreover, the electronic and steric effects of pyrazole-based ligands can be easily fine-tuned by changing the substituents on the pyrazolyl ring [20, 21]. The pyrazolyl group is introduced to the NHCs via two general approaches; as a pendant substituent attached to the side-arm of NHCs by the alkyl linker [12–17] and as a bridge between two NHCs [22–24]. Examples of the pyrazolyl group attached to NHCs by an aryl linker are very limited [25–27]. Our recent investigations have indicated that NHCs based on 1-[2-(pyrazol-1-yl)phenyl]-imidazole exhibit versatile coordination modes in their silver complexes [27], and these silver complexes possess highly effective catalytic activity, which inspires us to exploit other transition metal complexes of these pyrazolyl-functionalized NHCs. As an extension of this work, we herein report the synthesis of their palladium complexes. These palladium complexes showed highly efficient catalytic activity for the carbon–carbon coupling reactions under air atmosphere.

Experimental

NMR (^{1}H and ^{13}C) were recorded on a Bruker 400 spectrometer, and the chemical shifts were reported in ppm with respect to the reference (internal $SiMe_4$ for ^{1}H and ^{13}C NMR spectra). The assignments were confirmed by standard Bruker gradient enhanced HMBC and HMQC pulse sequences. Element analyses were carried out on an Elementar Vairo EL analyzer. Melting points were measured with an X-4 digital micro melting-point apparatus and were uncorrected. 1-[2-(3,5-dimethylpyrazol-1-yl)phenyl]imidazole (DPI) [27], *N*-[2-(pyrazol-1-yl)phenyl]-*N*′-benzylimidazolium

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chloride (PBCl) [27], and *N*-[2-(3,5-dimethylpyrazol-1-yl)phenyl]-*N*′-benzylimidazolium chloride (DPBCl) [27] were prepared according to the published methods.

Synthesis of *N*-[2-(pyrazol-1-yl)phenyl]-*N*′-benzylimidazol-2-ylidene palladium chloride (**1**)

A mixture of PBCl (0.50 g, 1.5 mmol) and Ag_2O (0.35 g, 1.5 mmol) in CH_2Cl_2 (20 mL) was stirred for 24 h at room temperature in the absence of light. Then, $Pd(CH_3CN)_2Cl_2$ (0.39 g, 1.5 mmol) was added. The reaction mixture was continuously stirred for 24 h. The solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica using ethanol/dichloromethane (1/20 v/v) as the eluent. The yellow eluate was concentrated to dryness to give a slightly yellow solid sample of **1**. Yield: 0.43 g (60 %); m.p. 195–197 °C. ^{1}H NMR (400 MHz, DMSO-d_6): δ 5.39 (d, $J = 14.6$ Hz, 1H, CH_2), 6.05 (d, $J = 14.6$ Hz, 1H, CH_2), 6.69 (s, br, 1H, H^4 of pyrazole), 7.36–7.44 (m, 3H, *meta*- and *para*-protons of C_6H_5), 7.56 (d, $J = 7.2$ Hz, 2H, *ortho*-protons of C_6H_5), 7.67 (s, br, 1H, H^3 of pyrazole), 7.75–7.87 (m, 4H, protons of C_6H_4 and imidazole), 7.93 (d, $J = 4.0$ Hz, 2H, C_6H_4), 8.39 (s, br, 1H, H^5 of pyrazole). ^{13}C NMR (100 MHz, DMSO-d_6): δ 53.0 (CH_2), 109.2 (C^4 of pyrazole), 124.0 and 124.1 (carbons of imidazole), 127.6 and 128.7 (*ortho*-carbons of C_6H_4), 128.2 (*para*-carbon of C_6H_5), 128.3 (*ortho*-carbons of C_6H_5), 128.8 (*meta*-carbons of C_6H_5), 130.6 and 131.7 (*meta*-carbons of C_6H_4), 132.7 and 132.9 (C_6H_4), 136.6 (C^5 of pyrazole), 136.8 (C_6H_5), 145.0 (C^3 of pyrazole), 151.7 ($C_{carbene}$). Anal. Calcd for $C_{19}H_{16}Cl_2N_4Pd$: C, 47.8; H, 3.4; N, 11.7. Found: C, 47.5; H, 3.4; N, 11.6.

Synthesis of *N*-[2-(3,5-dimethylpyrazol-1-yl)phenyl]-*N*′-benzylimidazol-2-ylidene palladium chloride (**2**)

This compound was obtained similarly using DPBCl instead of PBCl as described above for **1** as a slightly yellow solid. Yield: 46 %; m.p. 272–274 °C. ^{1}H NMR (400 MHz, DMSO-d_6): δ 2.06 (s, 3H, 5-CH_3), 2.14 (s, 3H, 3-CH_3), 5.42 (d, $J = 15.4$ Hz, 1H, CH_2), 6.03 (d, $J = 15.4$ Hz, 1H, CH_2), 6.29 (s, 1H, H^4 of pyrazole), 7.07–7.16 (m, 2H, *meta*-protons of C_6H_5), 7.33–7.37 (m, 2H, *ortho*-protons of C_6H_5), 7.39 (d, $J = 2.0$ Hz, 1H, *para*-proton of C_6H_5), 7.69 and 7.85 (d, d, $J = 2.0$ Hz, 1H, 1H, protons of imidazole), 7.81–7.84 and 7.90–7.94 (m, m, 2H, 2H, C_6H_4). ^{13}C NMR (100 MHz, DMSO-d_6): δ 12.4 (3-CH_3), 14.0 (5-CH_3), 52.5 (CH_2), 108.8 (C^4 of pyrazole), 123.7 and 124.3 (carbons of imidazole), 126.9 (*meta*-carbons of C_6H_5), 127.7 and 129.5 (*ortho*-carbons of C_6H_4), 127.9 (*para*-carbon of C_6H_5), 128.8 (*ortho*-carbons of C_6H_5), 130.1 and 131.7 (*meta*-carbons of C_6H_4), 131.2 and 134.6 (C_6H_4), 136.9 (C_6H_5), 145.0 (C^5 of pyrazole), 152.0 (C^3 of pyrazole), 152.4 ($C_{carbene}$). Anal. Calcd for $C_{21}H_{20}Cl_2N_4Pd$: C, 49.9; H, 4.0; N, 11.1. Found: C, 50.0; H, 3.9; N, 11.1.

Synthesis of *N*-[2-(3,5-dimethylpyrazol-1-yl)phenyl]-*N*′-isopropylimidazolium iodide

A mixture of DPI (0.47 g, 2 mmol) and isopropyl iodide (0.24 mL, 2.4 mmol) in CH_3CN (5 mL) was stirred and heated at reflux for 24 h. After cooling to room temperature, ethyl acetate (10 mL) was added. A yellow precipitate was formed, which was filtered off and washed with dried ethyl ether to give a yellow solid. Yield: 0.80 g (98 %); m.p. 184–186 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.63 (d, $J = 6.7$ Hz, 6H, $CH(CH_3)_2$), 2.08 (s, 3H, 5-CH_3), 2.18 (s, 3H, 3-CH_3), 5.26 (septet, $J = 6.7$ Hz, 1H, $CH(CH_3)_2$), 5.97 (s, 1H, H^4 of pyrazole), 7.07 and 7.68 (s, s, br, br, 1H, 1H, protons of imidazole), 7.48–7.54 (m, 1H), 7.69–7.72 (m, 2H) and 8.11–8.13 (m, 1H) (C_6H_4), 10.29 (s, 1H, proton of imidazolium). ^{13}C NMR (100 MHz, $CDCl_3$): δ 11.5 (5-CH_3), 13.4 (3-CH_3), 23.1 ($CH(CH_3)_2$), 53.7 ($CH(CH_3)_2$), 107.2 (C^4 of pyrazole), 119.9 and 122.7 (carbons of imidazole), 126.8 and 129.4 (*ortho*-carbons of C_6H_4), 131.0 and 131.4 (*meta*-carbons of C_6H_4), 131.5 and 133.5 (C_6H_4), 141.8 (C^5 of pyrazole), 150.6 (C^3 of pyrazole). Anal. Calcd for $C_{17}H_{21}IN_4$: C, 50.0; H, 5.2; N, 13.7. Found: C, 50.5; H, 4.8; N, 13.5.

Synthesis of *N*-[2-(3,5-dimethylpyrazol-1-yl)phenyl]-*N*′-isopropylimidazol-2-ylidene palladium iodide acetate (**3**)

A mixture of *N*-[2-(3,5-dimethylpyrazol-1-yl)phenyl]-*N*′-isopropylimidazolium iodide (0.41 g, 1 mmol) and $Pd(OAc)_2$ (0.22 g, 1 mmol) in CH_2Cl_2 (20 mL) was stirred at room temperature for 24 h. The reaction mixture was filtered. The filtrate was concentrated to dryness and washed with dried ethyl ether to give a yellow solid sample of **3**. Yield: 0.49 g (86 %); m.p. 134–136 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.41 (d, $J = 6.4$ Hz, 3H, $CH(CH_3)_2$), 1.51 (d, $J = 6.4$ Hz, 3H, $CH(CH_3)_2$), 1.82 (s, 3H, 5-CH_3), 2.04 (s, 3H, 3-CH_3), 2.14 (s, 3H, $COCH_3$), 5.69–5.77 (m, 1H, $CH(CH_3)_2$), 6.03 (s, 1H, H^4 of pyrazole), 7.04 and 7.17 (s, s, br, br, 1H, 1H, protons of imidazole), 7.61–7.76 (m, 4H, C_6H_4). ^{13}C NMR (100 MHz, $CDCl_3$): δ 12.9 (5-CH_3), 13.8 ($COCH_3$), 14.1 (3-CH_3), 21.5 and 24.2 ($CH(CH_3)_2$), 31.6 ($CH(CH_3)_2$), 108.7 (C^4 of pyrazole), 118.8 and 122.9 (carbons of imidazole), 127.1, 130.2, 130.3 and 131.3 (*ortho*- and *meta*-carbons of C_6H_4), 132.8 and 135.0 (C_6H_4), 143.5 (C^5 of pyrazole), 151.0 (C^3 of pyrazole), 152.4 ($C_{carbene}$).

Anal. Calcd for $C_{21.95}H_{28.93}Cl_2I_{1.02}N_4O_{3.95}Pd$: C, 36.7; H, 4.1; N, 7.8. Found: C, 36.6; H, 3.7; N, 7.5.

Crystal structure determinations

Crystals of **1** and **3** suitable for X-ray analyses were obtained by slow diffusion of hexane into their CH_2Cl_2 solutions at 4 °C. The C(1), C(10), C(13)–C(19), N(1) and N(4) atoms in **1** were found to be disordered. Satisfactory results were obtained when these atoms were given occupancy factors of 0.598, and C(1)′, C(10)′, C(13)′–C(19)′, N(1)′ and N(4)′ atoms were given occupancy factors of 0.402. The geometry of disordered groups was restricted, and isotropic displacement parameters for all disordered atoms were used. Crystals of **3** contained one CH_3CO_2H and one CH_2Cl_2 molecules. The acetate position was partly replaced by iodide (2.4 %) in this complex. All intensity data were collected on a Rigaku Saturn CCD detector at 113(2) K. Semi-empirical absorption corrections were applied using the CrystalClear program [28]. The structures were solved by direct methods and difference Fourier map using SHELXS of the SHELXTL package and refined with SHELXL [29] by full-matrix least-squares on F^2. A summary of the fundamental crystal data for **1** and **3** is listed in Table 1.

Table 1 Crystal data and refinement parameters for complexes **1** and **3**

Complex	**1**	**3**.$CH_3CO_2H.CH_2Cl_2$
Formula	$C_{19}H_{16}Cl_2N_4Pd$	$C_{21.95}H_{28.93}Cl_2I_{1.02}N_4O_{3.95}Pd$
Formula weight	477.66	719.32
Crystal size (mm)	0.24 × 0.22 × 0.18	0.20 × 0.18 × 0.12
λ (MoKα) (Å)	0.71073	0.71073
Crystal system	Triclinic	Monoclinic
Space group	$P\bar{1}$	$P2_1/n$
a (Å)	9.397(3)	8.403(2)
b (Å)	14.846(4)	22.464(6)
c (Å)	15.915(5)	15.206(4)
α (°)	65.95(1)	90
β (°)	89.59(2)	94.722(5)
γ (°)	74.01(1)	90
V (Å)^3	1,935.1(10)	2,860.6(14)
Z	4	4
D_c (g.cm^{-3})	1.640	1.670
F(000)	952	1,418
μ (mm^{-1})	1.245	1.974
θ Range (°)	1.41–29.11	1.62–27.89
No. of measured reflections	26,838	29,171
No. of unique reflections (R_{int})	10,300 (0.0399)	6,744 (0.0436)
No. of observed reflections with ($I > 2\sigma(I)$)	6,923	5,831
No. of parameters	405	318
GOF	1.052	1.034
Residuals R_1, wR_2	0.0505, 0.1170	0.0546, 0.1594

General procedure for the catalytic Suzuki–Miyaura reaction

In a typical experiment, the mixture of $PhB(OH)_2$ (0.15 g, 1.2 mmol), ArX (1 mmol), Cs_2CO_3 (0.66 g, 2.0 mmol) and NHC–Pd complex (n mol%) was charged into a reaction tube (10 mL) with 2 mL of mixed solvent of isopropyl alcohol and water (1/1 v/v) or pure water. After the reaction mixture was stirred at 80 °C for a given time, water (10 mL) was added. The reaction mixture was extracted with ethyl ether (3 × 10 mL). The organic phases were combined and dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica using hexane as the eluent to give the corresponding diphenyl derivatives. When ArX was 4-bromoacetophenone, ethyl acetate was used as the eluent. The products were confirmed by comparison with NMR spectroscopic data in the literature.

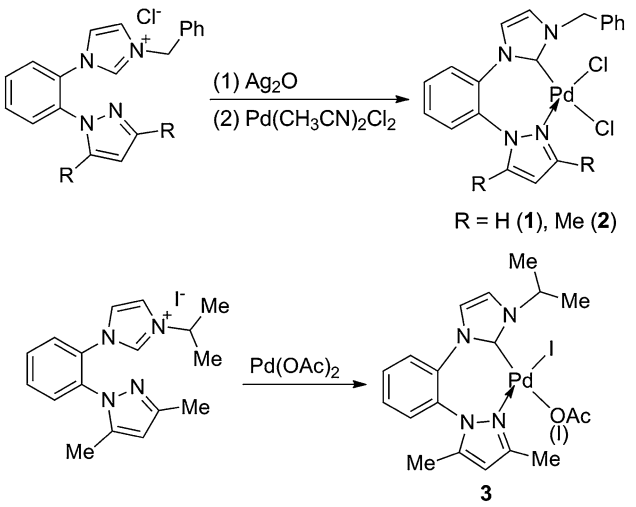
General procedure for the catalytic Mizoroki–Heck reaction

In a typical experiment, a mixture of ArX (1 mmol), styrene (0.14 mL, 1.2 mmol), K_2CO_3 (0.28 g, 2.0 mmol) and NHC–Pd complex (n mol%) was charged into a reaction tube (10 mL) with 2 mL of mixed solvent of DMF and water (3/1 v/v). Then, the reaction mixture was stirred at 120 °C for 24 h. After cooling to room temperature, the solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica using ethyl acetate/hexane as the eluent to give the corresponding *trans*-1,2-diarylethene, which was confirmed by comparison with NMR spectroscopic data in literature.

Results and discussion

Synthesis and characterization of NHC–Pd complexes

The pyrazolyl-functionalized NHC–Pd complexes (**1**) and (**2**) were easily obtained by the carbene transfer reaction of the corresponding NHC–Ag complexes with $Pd(CH_3CN)_2Cl_2$ (Scheme 1), while complex **3** was obtained by the direct reaction of the imidazolium salt with $Pd(OAc)_2$. Complexes **1**–**3** were stable to air and moisture, and they were soluble in chlorinated solvents. These three



Scheme 1 Synthesis of pyrazolyl-functionalized NHC–Pd complexes

complexes have been characterized by elemental analyses and NMR spectroscopy.

Compared with the spectra of their imidazolium salt precursors, a notable change in the ^{1}H NMR spectra of these three complexes was the disappearance of the characteristic proton signal of imidazolium, indicating the formation of NHC–Pd complexes along with the deprotonation of the acidic hydrogen. In addition, an obvious carbene carbon signal was observed around 152 ppm in their ^{13}C NMR spectra, which is similar to those of reported NHC–Pd complexes [30, 31]. The ^{1}H NMR spectra of **1** and **2** indicated the methylene protons of the benzyl group were nonequivalent, and an AB system was observed at room temperature. At the same time, two sets of ^{1}H and ^{13}C NMR signals corresponding to the isopropyl methyl groups were observed in complex **3**. These results suggest the presence of large steric repulsion in these three complexes, possibly owing to the chelating coordination of the NHC ligands, which prevents the free rotation of substituents.

Crystal structures of **1** and **3**

The molecular structures of **1** and **3** have been further confirmed by X-ray structural analyses. The X-ray crystal structure of complex **1** consists of two crystallographically independent molecules with similar structural parameters. One of them is presented in Fig. 1. The crystal structure of complex **3** is shown in Fig. 2. The pyrazolyl-functionalized NHCs act as [N,C] chelating bidentate ligands through the carbene carbon and pyrazolyl nitrogen atoms coordinating to the palladium atom in these two complexes, resulting in a seven-membered metallocycle with boat-like conformation. The palladium atom exhibits a four-coordinate

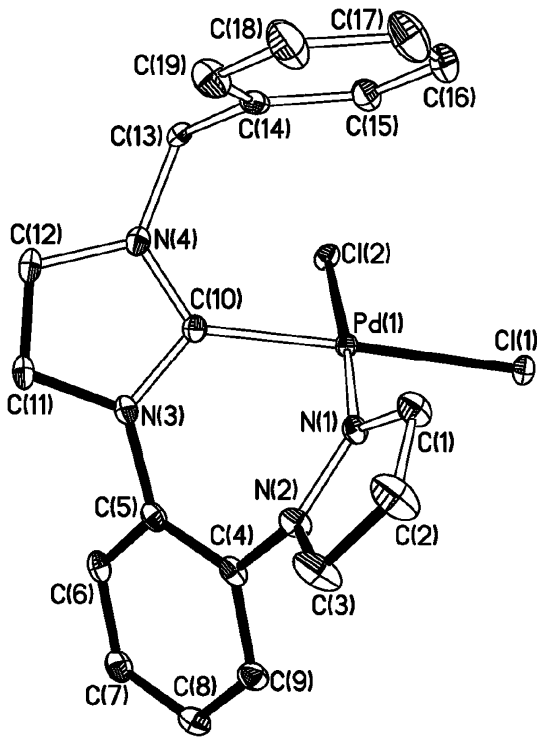


Fig. 1 Molecular structure of **1**. The thermal ellipsoids are drawn at the 30 % probability level. Selected bond distances (Å) and angles (°): Pd(1)–C(10) 1.979(4), Pd(1)–N(1) 2.004(4), Pd(1)–Cl(1) 2.336(1), Pd(1)–Cl(2) 2.321(1) and C(10)–Pd(1)–N(1) 86.4(2), C(10)–Pd(1)–Cl(2) 89.9(1), C(10)–Pd(1)–Cl(1) 176.0(1), N(1)–Pd(1)–Cl(1) 89.6(1), Cl(1)–Pd(1)–Cl(2) 94.07(4), N(4)–C(13)–C(14) 113.9(5)

slightly distorted square-planar coordination geometry. The deviation of the palladium atom from the square plane is only 0.0040 Å in **1** and 0.0252 Å in **3**, respectively. The Pd–C and Pd–N bond distances are 1.979(4) Å and 2.004(4) Å in **1**, respectively, similar to the Pd–C (1.956(5) Å) and Pd–N (2.037(5) Å) bond distances in **3**. These values are comparable to those of other known pyrazolyl-functionalized NHC–Pd complexes, such as those in $LPdCl_2$ (Pd–C 1.970(4) Å and Pd–N 2.042(3) Å, L = 3-butyl-1-(pyrazolylmethyl)imidazol-2-ylidene) [16] and $L'_2Pd_2Br_2$ (av. Pd–C 1.965 Å and av. Pd–N 2.097 Å, L′ = *N*-[bis(3,5-dimethylpyrazol-1-yl)methyl]phenyl-*N*′-benzylimidazol-2-ylidene) [26].

The dihedral angles between the phenyl plane with pyrazolyl and imidazolyl planes are significantly different in these two complexes, possibly owing to the different substituents in the third position of the imidazolyl ring and the different anions in the palladium atom. The dihedral angle between the phenyl plane and the pyrazolyl plane is 52.7° in **1**, smaller than the corresponding dihedral angle in **3** (58.7°), while the dihedral angle between the phenyl plane and the imidazolyl plane is 126.4° in **1**, larger than that in **3** (123.8°). In addition, the electronegative oxygen is

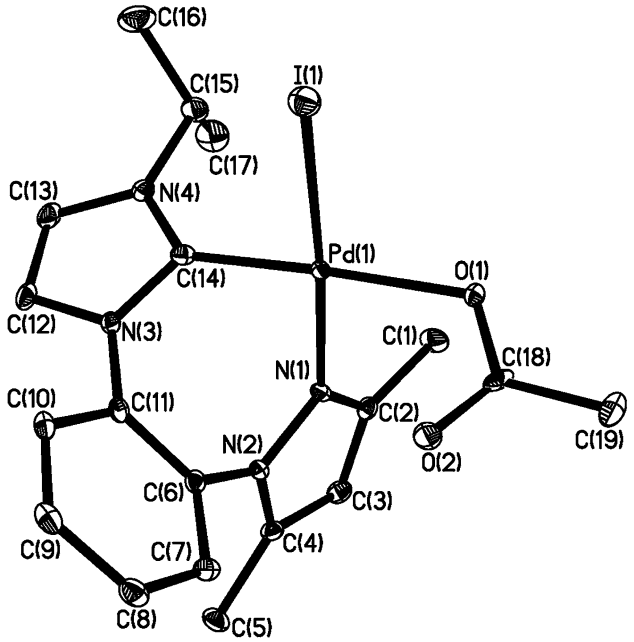


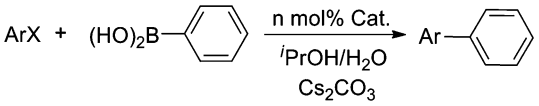
Fig. 2 Molecular structure of **3**. The thermal ellipsoids are drawn at the 30 % probability level. The uncoordinated solvents and the part incorporation of iodide have been deleted for clarity. Selected bond distances (Å) and angles (°): Pd(1)–I(1) 2.5759(7), Pd(1)–C(14) 1.956(5), Pd(1)–N(1) 2.037(5), Pd(1)–O(1) 2.083(4), C(18)–O(1) 1.308(10), C(18)–O(2) 1.246(12) and C(14)–Pd(1)–N(1) 85.4(2), C(14)–Pd(1)–O(1) 174.9(2), C(14)–Pd(1)–I(1) 90.7(2), N(1)–Pd(1)–I(1) 175.7(1), C(16)–C(15)–C(17) 113.5(6), O(1)–C(18)–O(2) 121.2(8), O(2)–C(18)–C(19) 123.0(8)

trans to the carbene carbon atom in **3**, like those in other pyrazolyl-functionalized NHC–Pd complexes [14]. The angle C(14)–Pd(1)–O(1) is 174.9(2)° in **3**. It is worth noting that some angles around the C(13) atom in **1** (such as the angle N(4)–C(13)–C(14) of 113.9(5)°) and the C(15) atom in **3** (such as the angle C(16)–C(15)–C(17) of 113.5(6)°) markedly deviate from the tetrahedral geometry of the sp^3 hybridized carbon atom, which reflects the presence of the steric repulsion between the benzyl in **1** and isopropyl in **3** with other substituents in these complexes, as also indicated by their NMR spectra.

The catalytic activity of complexes **1**–**3**

Palladium-catalyzed cross-coupling reaction has become an extremely powerful tool for the formation of carbon–carbon and carbon–heteroatom bonds. NHC–Pd complexes have been successfully applied in this area [32, 33], since Herrmann and co-works reported well-defined NHC–Pd complexes as efficient catalysts in the Heck reaction [4]. Additionally, NHC–metal complexes for catalysis in aqueous media have received considerable attention because water is an attractive benign solvent [34]. Some cross-coupling reactions catalyzed by NHC–Pd complexes have been successfully performed in water in recent years

Table 2 Catalytic activity of NHC–Pd complexes in the Suzuki–Miyaura reaction



Entry	ArX	Cat.	*n*	*t*/h	Yield (%)[a,b]
1[c]	C_6H_5Br	**1**	0.01	1	99
2[c]	C_6H_5Br	**2**	0.01	1	98
3[c]	C_6H_5Br	**3**	0.1	12	99
4	C_6H_5Br	**1**	0.01	1	97
5	C_6H_5Br	**2**	0.01	1	96
6	C_6H_5Br	**3**	0.1	12	97
7	*o*-$CH_3OC_6H_4Br$	**2**	0.01	12	94
8	*o*-$CH_3OC_6H_4Br$	**3**	0.01	12	88
9	*o*-$C_2H_5C_6H_4Br$	**1**	0.1	2	90
10	*o*-$C_2H_5C_6H_4Br$	**2**	0.1	2	97
11	*o*-ClC_6H_4Br	**1**	0.1	24	83
12	*o*-ClC_6H_4Br	**2**	0.1	24	86
13	*m*-$CH_3OC_6H_4Br$	**1**	0.1	24	96
14	*m*-$CH_3OC_6H_4Br$	**2**	0.1	24	95
15	*m*-FC_6H_4Br	**1**	0.005	12	99
16	*m*-FC_6H_4Br	**2**	0.005	12	84
17	*m*-FC_6H_4Br	**3**	0.1	12	87
18[c]	*m*-FC_6H_4Br	**1**	0.005	4	99
19[c]	*m*-FC_6H_4Br	**2**	0.01	10	82
20	*p*-$BrC_6H_4COCH_3$	**1**	0.1	12	98
21	*p*-$BrC_6H_4COCH_3$	**2**	0.1	12	96
22	*p*-$BrC_6H_4COCH_3$	**3**	0.1	12	90
23	*p*-$BrC_6H_4COCH_3$	**1**	0.1	12	98
24	*p*-$BrC_6H_4COCH_3$	**2**	0.1	12	99
25[c]	*p*-$BrC_6H_4COCH_3$	**3**	0.1	12	92
26[c]	1-bromonaphthalene	**1**	0.01	10	88
27[c]	1-bromonaphthalene	**2**	0.01	12	93
28	1-bromonaphthalene	**3**	0.01	12	90
29	2-bromopyridine	**1**	0.1	24	69
30	2-bromopyridine	**2**	0.1	24	68
31	2-bromopyridine	**3**	0.1	24	36

[a] Isolated yield

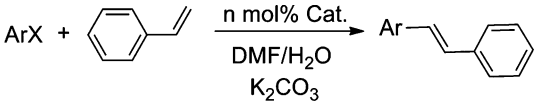
[b] Average of two runs

[c] Water as the solvent

[31, 34–38]. Herein, our studies showed that complexes **1**–**3** exhibited highly effective catalytic activities in the Suzuki–Miyaura (Table 2) and Mizoroki–Heck (Table 3) coupling reactions in water or aqueous/organic media under air atmosphere.

The initial cross-coupling reaction between PhBr and $PhB(OH)_2$ was performed in pure water using Cs_2CO_3 as the base at 80 °C. The corresponding coupled product was obtained in excellent isolated yield when 0.01 mol% of **1** or **2** as well as 0.1 mol% of **3** was used as the catalyst

Table 3 Catalytic activity of NHC–Pd complexes in the Mizoroki–Heck reaction



Entry	ArX	Cat.	*n*	Yield (%)[a,b]
1	C_6H_5Br	**1**	0.5	67
2	C_6H_5Br	**2**	0.5	89
3	C_6H_5Br	**3**	0.5	75
4	*o*-$CH_3OC_6H_4Br$	**1**	1.0	74
5	*o*-$CH_3OC_6H_4Br$	**2**	1.0	95
6	*o*-$CH_3OC_6H_4Br$	**3**	1.0	89
7	*o*-$C_2H_5C_6H_4Br$	**1**	1.0	95
8	*o*-$C_2H_5C_6H_4Br$	**2**	1.0	57
9	*o*-$C_2H_5C_6H_4Br$	**3**	1.0	79
10	*m*-FC_6H_4Br	**1**	1.0	99
11	*m*-FC_6H_4Br	**2**	1.0	99
12	*m*-$CH_3OC_6H_4Br$	**1**	1.0	92
13	*m*-$CH_3OC_6H_4Br$	**2**	1.0	80
14	*m*-$CH_3OC_6H_4Br$	**3**	1.0	85
15	*m*-BrC_6H_4CHO	**1**	1.0	99
16	*m*-BrC_6H_4CHO	**2**	1.0	96
17	*m*-BrC_6H_4CHO	**3**	1.0	85
18	*p*-$BrC_6H_4COCH_3$	**1**	0.5	92
19	*p*-$BrC_6H_4COCH_3$	**2**	0.5	86
20	*p*-$BrC_6H_4COCH_3$	**3**	0.5	99
21	2,4,6-$Me_3C_6H_2Br$	**1**	0.5	84
22	2,4,6-$Me_3C_6H_2Br$	**2**	0.5	40
23	1-bromonaphthalene	**1**	0.5	95
24	1-bromonaphthalene	**2**	0.5	95
25	1-bromonaphthalene	**3**	1.0	97
26	2-bromopyridine	**1**	1.0	44
27	2-bromopyridine	**2**	1.0	23
28	2-bromopyridine	**3**	1.0	29
29	2-bromothiophene	**1**	1.0	85
30	2-bromothiophene	**2**	1.0	45
31	2-bromothiophene	**3**	1.0	52
32	C_6H_5I	**2**	0.5	99

[a] Isolated yield

[b] Average of two runs

(Table 2, entries 1–3). This cross-coupling reaction could also proceed smoothly to give the expected product in the co-solvent of isopropyl alcohol and water (1/1 v/v) (Table 2, entries 4–6). Taking into account the solubility of the catalysts and substrates, other cross-coupling reactions of aryl halide with $PhB(OH)_2$ were carried out in the co-solvent of isopropyl alcohol and water (Table 2, entries 7–17, 20–24 and 28–31). Almost quantitative yield was obtained when only 0.005 mol% of **1** was used as the catalyst for the reaction of *m*-FC_6H_4Br (Table 2, entry 15). Furthermore, the coupling reaction proceeded significantly faster upon using pure water as the solvent (Table 2, entry 18) [25]. The cross-coupling reactions of other substituted aryl bromides could give moderate to good yields, upon prolonging the reaction time or increasing the loading amount of catalysts. The data of Table 2 revealed that complexes **1** and **2** possess higher catalytic activity than complex **3**. In most cases, no obvious catalytic activity difference was observed between **1** and **2**, indicating that the substituents on the pyrazolyl ring have slight influences on the catalytic activities of the complexes. This is different from that in pyridyl-supported tridentate pyrazolyl-functionalized NHC–Pd complexes, in which the catalytic activity was obviously decreased by the substituents on the pyrazolyl ring [25]. Under the present conditions, these complexes showed relatively low catalytic activity for the coupling reaction of 2-bromopyridine (Table 2, entries 29–31).

Complexes **1–3** also showed good catalytic activity for the Heck reaction between aryl halides and styrene (Table 3). Moderate to excellent yields were obtained when 0.5 mol% of complex was used as the catalyst (Table 3, entries 1–3, 18–24 and 32). All tested aryl halides gave satisfactory yields when the loading amount of catalyst was increased to 1.0 mol% (Table 3, entries 4–17 and 25). It can be observed from Table 3 that complex **1** shows higher catalytic activity than complex **2** in most cases, suggesting that the substituents on the pyrazolyl ring decrease the catalytic activity of complex **2**, presumably as a result of steric and electronic effects of the substituents influencing the coordination/dissociation process of the pyrazolyl nitrogen to the palladium center [14]. Table 3 also reveals that the catalytic activity of complex **3** is comparable to that of complexes **1** and **2** in the Heck reaction. For example, essentially quantitative product yield was obtained for the coupling of 4-bromoacetophenone when 0.5 mol% of complex **3** was used as the catalyst (Table 3, entry 20), which may be the result of the acetato ligand stabilizing active species in the Heck reaction [39, 40]. In addition, for heteroaryl bromides (Table 3, entries 26–31), the yields still need to be further improved.

Conclusion

In a summary, three pyrazolyl-functionalized NHC–Pd complexes have been synthesized. The pyrazolyl-functionalized NHCs act as chelating *N*,*C*-bidentate ligands in these complexes. These complexes exhibit highly effective catalytic activities in the Suzuki–Miyaura and Mizoroki–Heck coupling reactions in water or aqueous/organic media under air atmosphere. Additionally, the substituents on the

pyrazolyl ring have no obvious influence on the catalytic activity of complexes in the Suzuki–Miyaura reaction, while these substituents decrease the catalytic activity of the complex in the Mizoroki–Heck reaction in most cases. Further studies on the structure–activity relationships of such catalysts are currently in progress.

Supplementary material

CCDC 959855 for **1** and 959856 for **3** contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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