

CHAPTER II

Synthesis of Benzimidazole Based Palladium-*N*-Heterocyclic Carbene Complexes as Useful Catalyst for C-C Cross-Coupling Reaction at Ambient Conditions

II.A. Introduction

Transition metal catalyzed C-C cross coupling reaction is an indispensable tool for the construction of C-C bond which plays an important role in fine chemical synthesis, medicinal chemistry, natural product synthesis as well as in the field of nanotechnology.¹ After isolation of stable *N*-heterocyclic carbene (NHC) by Arduengo *et. al.* in 1991,^{2a} it has led to numerous applications in the field of transition metal catalysis and has turned out to be a potentially active ligating agent.² Use of *N*-heterocyclic carbenes, as nucleophiles in organo catalytic reactions has also been well established.³ Despite the existence of several families of stable carbenes, only imidazole based carbenes and their metal complexes have found numerous applications so far.⁴ A common facet of all those NHC-metal complexes are having bulky substituents, specially adamantyl,^{5,7b} aryl,⁶ cyclohexyl,⁷ tert-butyl,⁸ etc. in 1,3 position of imidazole ring. Bulky group often plays several important roles viz., it assists to form strong σ -bond with metals, which results in high stability of the metal complex and it also facilitates the catalytic performances.^{9,7b} It is very rare where normal alkyl chain is used instead of bulky group specifically for NHC-metal complexation. Few reports are available in the literature where the presence of Pd-NHC complex with *N*-alkyl substituted imidazole has been detected as reactive intermediate, which catalyzes organic transformations in ionic liquid media.¹⁰

Various Pd-NHC complexes catalyzed Suzuki cross-coupling reactions already mentioned in chapter-I. However apart from the biaryls, biaryl ketones are also important moieties in many biologically active molecules, natural products, and pharmaceuticals.¹¹ One general approach for the synthesis of aryl ketones is the Friedel-Crafts acylation of substituted aromatic ring.¹²

Various palladium catalyzed methodologies have also developed for the synthesis of biaryl ketones. These includes carbonylative cross-coupling reaction of aryl iodides and aryl boronicacids,¹³ reaction between aryl boronicacids and carboxylic acid anhydrides.¹⁴

Aromatic ketones can also be effectively prepared by another cross-coupling reaction of aryl boronic acids with acid chlorides,¹⁵ and such method can avoid the disadvantages of other strategies such as the low regio-selectivity of Friedel-Crafts acylation and handling the toxic carbon monoxide or the needs of phosphine-based ligands.

II.B. Present work: Background, objective and strategy

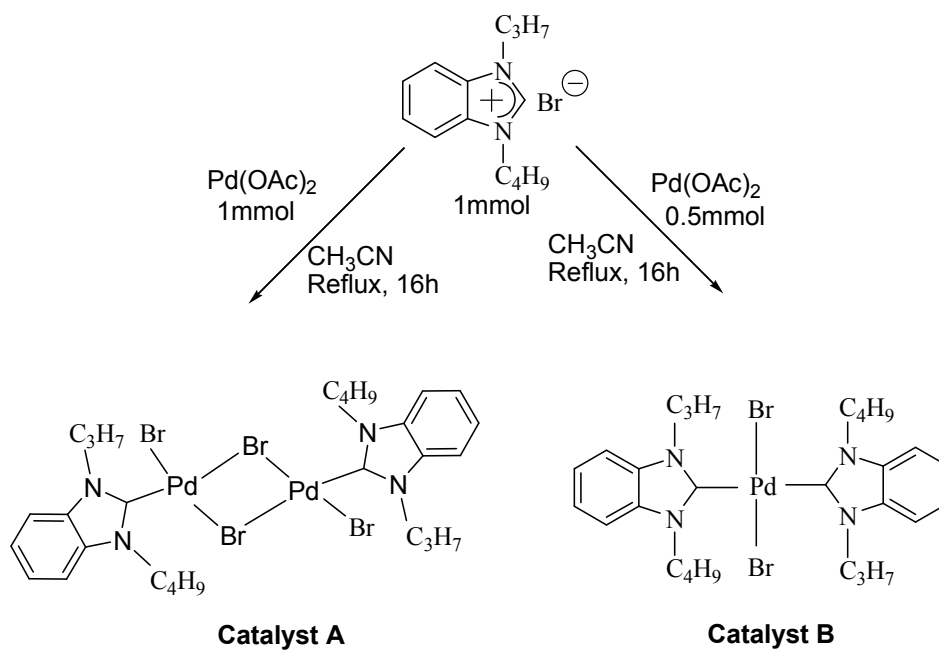
Benzimidazole-based NHC-metal complexes have recently been prepared instead of imidazole to accomplish high level of activity in Pd-catalyzed cross-coupling reactions.^{16, 17} Most importantly, the catalytic activity of benzimidazolidine NHCs can be tuned by simply introducing different functional group specifically at the 5 and 6 positions of the benzimidazole moiety.^{16a,b} It is anticipated that an enormous modification will make it more competent moiety. In the last few years, a number of benzimidazole-based palladiumNHC catalysts have been developed but those findings have limited applications in organic synthesis.^{16,17} Recent work by Huynh *et al.*^{17a} and Metallions *et al.*^{17b} on benzimidazole backbone palladium complexes require harsh conditions for catalyzing C-C cross-coupling reactions. It opens up the scope of stumbling onto more efficient and economic catalysts capable of catalyzing a reaction in mild condition.

In this chapter, we report the synthesis of a new air stable benzimidazole-based Pd-NHC complexes and their catalytic application in Suzuki cross-coupling reaction and for the synthesis of aryl ketones at ambient condition.

II.C. Present work: Result and discussion

II.C.1. Synthesis of benzimidazole-base Pd-NHC complexes

Butyl propyl benzimidazolium bromide was synthesized in approximately quantitative yield and was recrystallized from ethyl acetate.¹⁸ The solid salt was then refluxed with Pd(OAc)₂ in acetonitrile for 10 h. Depending on the ratio of the reagents (palladium salt and the ionic liquid), we have isolated two different products catalyst A and B (scheme-II.1).



Scheme-II.1: Synthesis of benzimidazole base-Pd-NHC complexes.

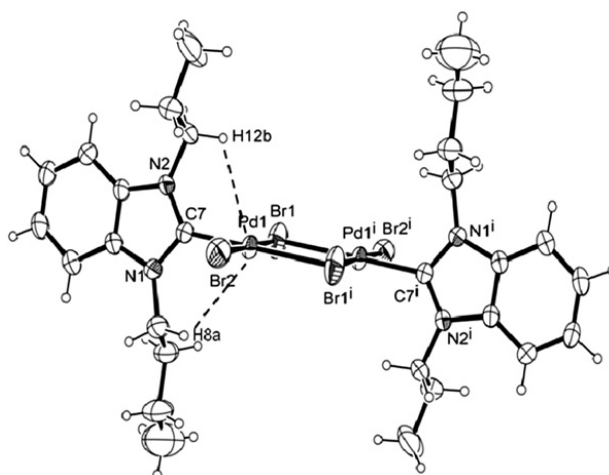


Figure-II.1: Catalyst-A

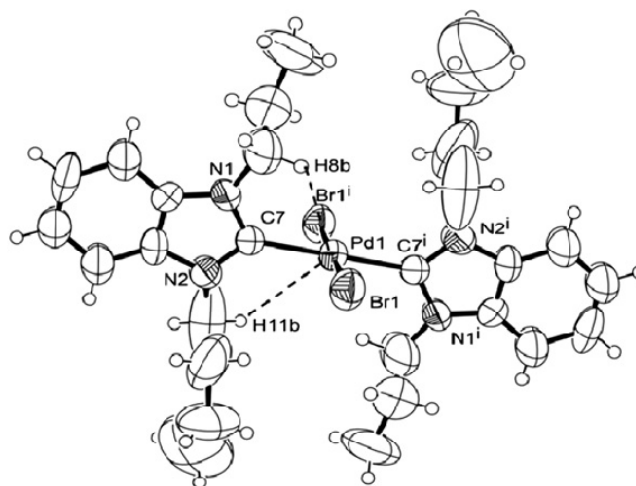


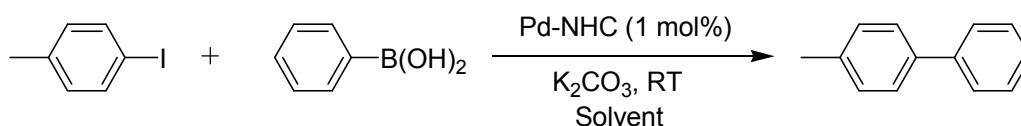
Figure-II.2: Catalyst-B

The structures are well characterized by single crystal X-ray crystallography. Catalyst A (figure-II.1) is crystallized in triclinic crystal system with $P-1$ space group while catalyst B (figure-II.2) has been crystallized in monoclinic crystal system with $P2_1/c$ space group. The catalysts display different structural features. Catalyst A is binuclear Pd(II) complex while catalyst B is a mononuclear Pd(II), whereas Pd(II) shows essentially square-planar geometry in both the structures. The structural feature of the catalyst A shows the bridged structure with two bromine as the bridging atoms that bridge two Pd(II) centre [Pd(II)⋯Pd(II) distance is 3.556 Å]. The carbon atom of NHC ligand has been organometallically coordinated to Pd(II) centers with Pd-C bond distance of 1.960 Å. The bond between Pd(II) and the bridging Br atom that is trans to NHC ligand is relatively elongated to some extent and this could be due to the trans effect of NHC ligand. It is also noteworthy, that the C–H protons (α -hydrogen atoms) of the alkyl groups are oriented towards the Pd(II) center resulting in relatively short C–H⋯Pd distances of 2.887 and 2.868 Å, respectively. The distances are typical to the preagostic interactions involving d8 systems. The origin of preagostic interactions is not clear however, it may involve weak overlap of the filled dz² or dxz orbital of the metal center with the C-H σ bond electrons. Catalyst B is mononuclear with essentially square-planar geometry around Pd(II) centre. The palladium center is coordinated by two carbene and two bromo ligands. Two NHC ligands are trans to each other with C-Pd(II)-C angle of 180°.

II.C.2. Suzuki cross-coupling reaction

With these novel Pd catalysts in hand, we envisioned to apply them in the construction of C-C bond *via* cross-coupling reaction. We commenced our studies using catalyst A for Suzuki coupling reaction where 4-iodo toluene and phenylboronic acid were selected as model coupling partners for optimizing the reaction.

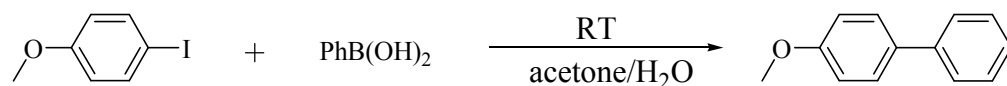
We started the reaction in toluene and the low conversion of desired product prompted us to look for the suitable solvent for this reaction. A screening of different solvents was then carried out to find the best condition. The detailed optimization results are summarized in table 1. Solvents like dioxane, acetonitrile, ethanol and water were found unsuitable for this reaction. A mixture of acetone/water proved to be the best solvent combination which leads to the desired product in 97 % yield within 45 min at ambient condition (table-II.1, entry 4).

Table-II.1: Optimization of Suzuki coupling between 4-iodotoluene and phenylboronic acid.

Entry	Solvent (4 mL)	Time (h)	Yield(%) ^a
1	Toluene	1.00	40
2	Dioxane	3.00	78
3	Acetonitrile	3.00	66
4	Acetone : water(1:1)	0.75	97
5	Water ^b	1.50	40
6	Ethanol:Water (1:1)	1.00	60

Reaction conditions: 4-iodotoluene(1mmol), phenylboronic acid (1.2 mmol), K₂CO₃ (2 mmol), catalyst-A (1 mol%, 0.0096 g), room temperature. ^b Isolated yield after column chromatography. ^c 1equiv. of TBAB was used.

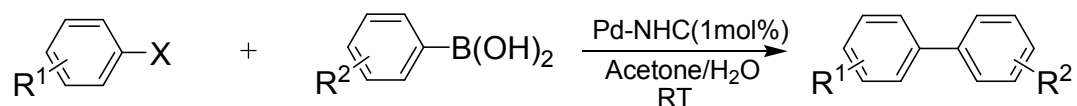
After the optimization of Suzuki reaction with catalyst A, we sought to check the catalytic performance of catalyst B as well. We considered similar reaction between 4-iodoanisole and phenylboronic acid with same palladium content under optimized condition and corresponding results are given in table-II.2 (entry 2, 3). It is noteworthy that catalyst A is much more effective compared to catalyst B. This is plausibly because catalyst A under the reaction condition undergoes dissociation to form monomer units (Pd-NHC) and this facilitates the oxidative coupling, the most important step for such cross-coupling reactions. In order to find the minimum concentration of the catalyst required for efficient catalytic activity, we again chose a reaction between 4-iodoanisole and phenyl boronic acid as the model case. Yield of the product decreases on decreasing the amount of catalyst in a fixed period of reaction. But the yield of the product increases by increasing the reaction time in case of both the catalysts (table-II.2, entry 2, 4). It has been found that the minimum concentration of catalyst A for effective coupling is 1 mol%.

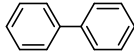
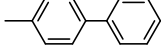
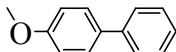
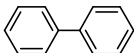
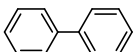
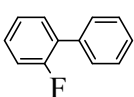
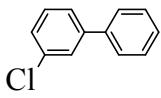
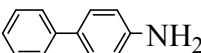
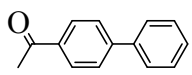
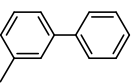
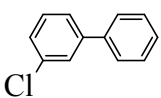
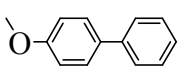
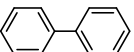
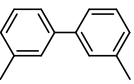
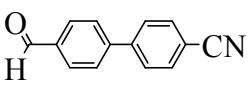
Table-II.2: Catalyst screening and loading experiment.

Entry	Catayst	Cat. Loading (mol%)	Pd-content (mol%)	Time (h)	yield (%) ^a
1	A	1.0	1.99	1.0	98
2	A	0.5	0.995	1.5	87
3	B	1.0	0.995	1.5	40
4	B	1.0	0.995	5.0	84
5	Pd(OAc) ₂	2.0	2.0	1.0	69
6	PdCl ₂	2.0	2.0	1.0	57
7	Pd ₂ (dba) ₃	1.0	2.0	1.0	78

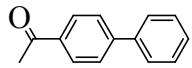
Reaction conditions: 4-iodoanisole (1mmol), phenylboronic acid (1.2 mmol) , K₂CO₃ (2 mmol). ^b Isolated yield after column chromatography.

In order to compare the catalytic efficiency of our newly developed Pd-NHC catalyst with commercially available Pd salts like Pd(OAc)₂, PdCl₂ and Pd₂(dba)₃, we were performed the same reaction under similar condition without altering palladium content. The results are shown in table-II.2 (entries 5-6) where the yields of the corresponding coupled products are obtained in the range of 57-78%.

Table-II.3: Suzuki cross coupling reaction of mono aryl halides.

Entry	R ¹	R ²	X	Time (min)	Yield (%) ^b	Product
1	H	H	I	45	98	
2	4-CH ₃	H	I	45	97	
3	4-OCH ₃	H	I	60	98	
4	2-CH ₃	H	I	45	93	
5	3-CH ₃	H	I	45	96	
6	2-F	H	I	60	97	
7	3-Cl	H	I	60	96	
8	4-NH ₂	H	I	45	98	
9	4-COCH ₃	H	Br	45	98	
10	3-CH ₃	H	Br	60	90	
11	3-Cl	H	Br	60	91	
12	4-OCH ₃	H	Br	60	98	
13	H	H	Br	60	99	
14	3-CH ₃	CH ₃	Br	60	90	
15	4-CN	CHO	Br	60	98	
16	4-COCH ₃	H	Cl	24hr	NR	

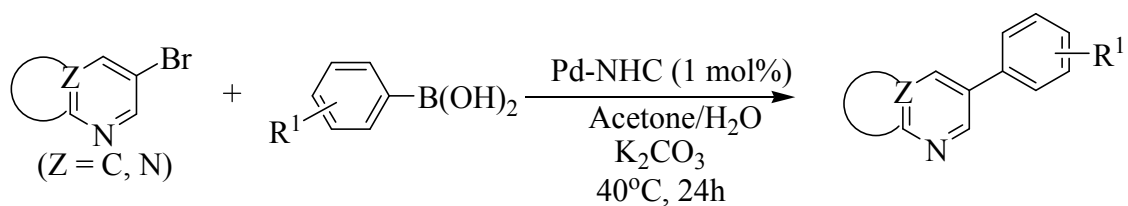
Continued.....

Entry	R ¹	R ²	X	Time (min)	Yield (%) ^b	Product
17 ^c	4-COCH ₃	H	Cl	24hr	NR	
18 ^d	4-COCH ₃	H	Cl	24hr	47	

Reaction conditions: aryl halide (1 mmol), arylboronic acid (1.2 mmol), K₂CO₃ (2 mmol), catalyst A (1 mol%), room temperature. ^b Isolated yield after column chromatography purification. ^c Reaction was carried out at 70°C. ^dDMF:water (1:1) was used as solvent and the reaction was carried out at 90°C.

With the optimized conditions in hand, we probed the scope of Suzuki reaction of different mono aryl halides with different arylboronic acids (table-II.3). Notably, both electron deficient as well as electron rich aryl halides provided the desired coupled products in excellent yield. Iodo and bromo arylhalides underwent this coupling reaction very smoothly. Several active functional groups such as -NH₂, -COCH₃, -CN, -Cl, -F remain dormant and allows selective Suzuki coupling (table-II.3, entry 8, 9, 15, 11, 6 respectively). On the other hand, sterically hindered aryl halides (table-II.3, entry 4 and 6) also result in the desired coupled product in excellent yield. In addition, 3-tolylboronic acids, 4-formylphenylboronic acid were also successfully coupled to form the corresponding substituted biphenyl without any side reaction (table-II.3, entry14 and 15). We also attempted the cross coupling reaction of activated aryl chloride but in this case we only have the marginal successes (table-II.3, entry 16-18).

Suzuki coupling for heteroaromatic system often needs harsh condition compared to aromatic system. We explored the possibility of the application of the catalyst in heteroaromatic systems. And accordingly, we made an attempt to carry out the Suzuki reaction at our optimized condition but yield of the desired product was not satisfactory (it lies between 40-50% even after continuing the reaction for 48 h). To overcome this shortcoming, we increased the reaction temperature to 40°C and the results are summarized in table 4. Bromo pyridine, pyrimidine and quinoline all underwent smooth reaction. 3-tolylboronic acid as well as electron deficient 4-fluoro phenylboronic acid also resulted in the desired product in 96 and 82% yield (table-II.4, entry-5 & 4) respectively.

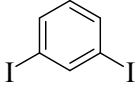
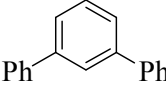
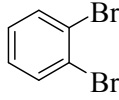
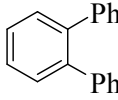
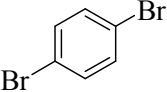
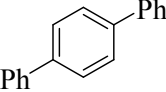
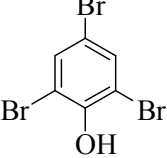
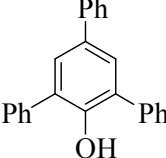
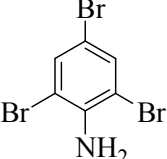
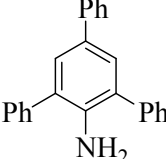
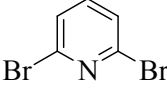
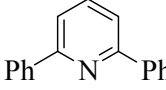
Table-II.4: Suzuki cross-coupling of hetero aryl halides

Entry	R ¹	Yield(%)	Product
1	H	83	
2	H	84	
3	H	88	
4	4-F	96	
5	3-CH ₃	82	

Reaction conditions: heteroaryl halide (1mmol), arylboronic acid (1.2 mmol), K₂CO₃ (2 mmol), catalyst A (1 mol %); Isolated yield after column chromatography purification.

To expand the scope of the catalyst, we ventured to use it for polyarylation and the results are summarized in table 5. Initially, we started with 1, 3-diiodobenzene which results in the corresponding *m*-terphenyl with 92% yield within 1.5 h at ambient condition. But in case of bromo compounds the reaction time is longer as iodide is a better leaving group compared to bromide. 1, 2-dibromobenzene results in the formation of *o*-terphenyl in 60% which may be due to the steric hindrance on the other hand 1, 4-dibromobenzene accomplished *p*-terphenyl in 90% yield. 2, 4, 6-tribromo phenol and aniline required longer time and yielded the desired product in 50 and 60% respectively (table-II.5, entry-4 and 5). Surprisingly, 2, 6-dibromopyridine also underwent the reaction smoothly resulting in 2, 6-diphenylpyridine in 90% yield at 40°C.

Table-II.5: Multi Suzuki cross coupling reaction in one step^a

Entry	Haloarene	Time (h)	Product	Yield (%) ^b
1		1.5		92
2		5		60
3		5		90
4		24		50
5		24		60
6 ^c		24		90

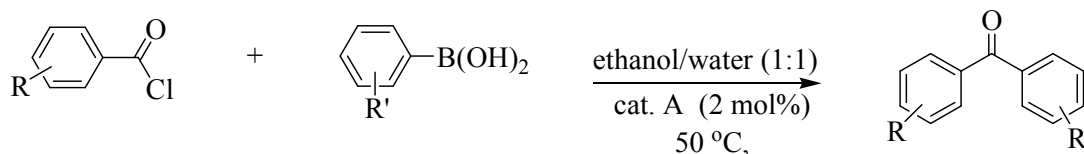
^a Reaction conditions: aryl halide (1 mmol), phenylboronic acid (1.2 mmol for each halide), K₂CO₃ (2 mmol for each halide), catalyst A (1 mol %), room temperature. ^b Isolated yield after column chromatography purification. ^c reaction was carried out at 40°C.

II.C.3. Synthesis of aryl ketone through the cross-coupling reaction of aryl chloride with arylboronic acid

After successful demonstration of the Suzuki coupling reaction, we further proceeded to find other suitable applications of the catalyst A and accordingly made an attempt to use our catalyst for aryl ketone synthesis from acid chloride. Recently Zhang *et al.*¹⁹ used ionically tagged benzimidazole Pd(II) complex for similar reactions but reported prolong reaction time (12 h at 60 °C). In our system, treatment of acid chloride with boronic acid in mixed solvent

(ethanol/water) at 50 °C in presence of the catalyst A resulted in the desired ketone in high yield within a couple of hours and corresponding results are displayed in table-II.6.

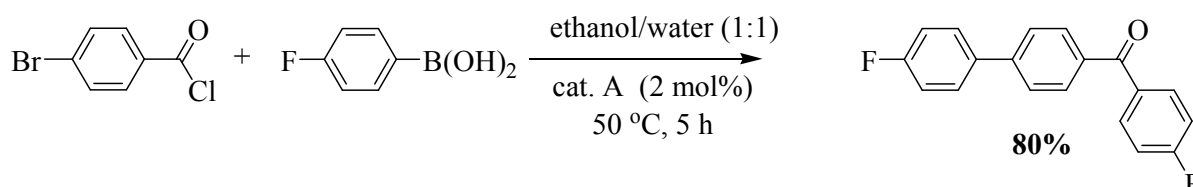
Table-II.6: Cross coupling reaction of acid chlorides with arylboronic acids^a



Entry	R	R'	Time	Yield ^b
1	R = H	R' = H	5 h	80 %
2	R = 4-F	R' = 4-F	2 h	96 %
3	R = 2-Cl	R' = H	5 h	78 %

^a Reaction conditions: arylacid chloride (1.2 mmol), arylboronic acid (1 mmol), K₂CO₃ (2 mmol). ^b Isolated yield after column chromatography.

It has been found that the presence of an electron withdrawing group in phenylboronic acid (table-II.6, entry-2) highly accelerated the reaction and resulted in 96 % yield of the corresponding aryl ketone within 2 h.



Scheme-II.2: Two different cross coupling in one pot.

In order to expand these promising initial results, we were tempted to perform two reactions in one pot. For that purpose we had designed an experiment attempting to consecutive couplings with different functional groups in one-pot reaction. Indeed, we were successful in consecutive one-pot coupling of 4-bromo benzoylchloride with 4-fluorophenylboronic acid leading to the formation of the double coupled product in 80% yield (scheme-II.2).

II.D. Conclusion

We have introduced benzimidazole-based Pd-NHC, a new air stable versatile catalyst which efficiently catalyzed Suzuki cross-coupling reaction as well as coupling of aryl acid chlorides with aryl boronic acids at ambient conditions in a wide variety of substrate. Our reaction conditions offer selective cross coupling which may often be a useful tool in synthetic chemistry. Future work will include studies aimed at further scope of the catalyst with regard to different kinds of related reactions.

II.E. Experimental

II.E.1. General consideration

Unless stated otherwise, all reagents such as Palladium acetate, aryl boronic acid, aryl halides, potassium carbonate, benzimidazole, alkyl halides and solvents were used as received from commercial suppliers. NMR spectra were recorded on 300 MHz spectrometer at 298 K and calibrations were done on the basis of solvent residual peak. Mass spectra were performed using ion trap mode. Elemental analysis were done in varioEL CHNS. Products were isolated using column chromatography on silica gel (60–120 mesh) and a mixture of petroleum ether (60-80°C)/ethyl acetate was used as an eluent. Reaction progress was monitored by silica gel TLC.

II.E.2. Preparation of Pd-NHC (Catalyst-A and Catalyst-B)

II.E.2a. Catalyst A

Butyl propyl benzimidazolium bromide (0.297 g, 1mmol) in 20 mL of acetonitrile was treated with palladium acetate (0.224 g, 1mmol). The mixture was allowed to react at 85 °C for 12 h. It was then filtered through celite to remove unreacted palladium. The resulting solution was then concentrated under reduced pressure to 3 mL. On addition of 15 mL of diethyl ether an orange crystal (Catalyst A) appeared and accordingly it was collected and dried under vacuum. Yield: 0.395 g, 74%

II.E.2b. Catalyst B

Butyl propyl benzimidazolium bromide (0.297 g, 1mmol) was taken in 20 mL acetonitrile and allowed to react with 0.112 g (0.5 mmol) of Pd(OAc)₂ at 85 °C for 12 h. Then the reaction mixture was cooled to room temperature and filtered through celite to remove unreacted palladium. The resulting solution was then concentrated under reduced pressure up

to 3 mL. On addition of 15 mL of diethyl ether a yellow crystal (Catalyst B) appeared and accordingly it was collected and dried under vacuum. Yield: 0.323 g, 85%

II.E.3. Spectral analysis of catalyst A and B

Catalyst A: Isolated as orange solid; [Found: C, 34.86; H, 4.11; N, 5.75. $C_{28}H_{40}Br_4N_4Pd_2$ requires C, 34.85; H, 4.18; N, 5.81 %]; R_f (25 % EtOAc/PET) 0.33; 1H NMR (300 MHz, $CDCl_3$) δ 7.39-7.43 (m, 4H), 7.29-7.33 (m, 4H), 5.30 (m, 8H), 2.17-2.30 (m, 8H), 1.59-1.69 (m, 4H), 1.12-1.21 (m, 12H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.2, 134.5, 134.4, 123.4, 110.6, 50.5, 48.8, 31.3, 22.9, 20.4, 13.9, 11.7.

Catalyst B: Isolated as yellow solid; [Found: C, 47.96; H, 5.69; N, 7.84. $C_{28}H_{40}Br_2N_4Pd$ requires C, 48.12; H, 5.77; N, 8.02 %]; R_f (25 % EtOAc/PET) 0.67; 1H NMR (300 MHz, $CDCl_3$) δ 7.29-7.33 (m, 4H), 7.16-7.20 (m, 4H), 4.69-4.77 (m, 8H), 2.15-2.26 (m, 8H), 1.46-1.55 (m, 4H), 0.99-1.11 (m, 12H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 181.1, 134.7, 134.6, 122.6, 110.4, 50.0, 48.3, 31.9, 23.2, 20.7, 14.0, 11.9.

II.E.3a Important crystal data of catalyst A

Empirical formula	$C_{28}H_{40}Br_4N_4Pd_2$
Formula Weight	965.04
Temperature	293 K
Wavelength	0.71073
Crystal system	Triclinic
Bond precision(C-C)	0.0138 Å
Space group	P - 1
Hall group	-P 1
Unit cell dimension	$a = 8.0876(6)$ Å $\alpha = 93.993(5)$ $b = 9.7280(7)$ Å $\beta = 107.059(4)$ $c = 12.0928(10)$ Å $\gamma = 112.229(4)$
Volume	Calculated = $824.24(12)$ Å ³ Reported = $824.23(11)$ Å ³
Density	1.944 g/cm ³

Z	1
Absorption coefficient	5.963 mm ⁻¹
F(000)	468.0
Completeness to theta = 30.60°	98.5%
Max. And min. Transmission	0.225 and 0.116
Correction method	Empirical
R(reflections)/wR2(reflections)	0.0558(2232)/0.2081(5003)

The crystal data of catalyst has deposited at Cambridge Crystallographic Data Centre. The CCDC reference number is **871899**.

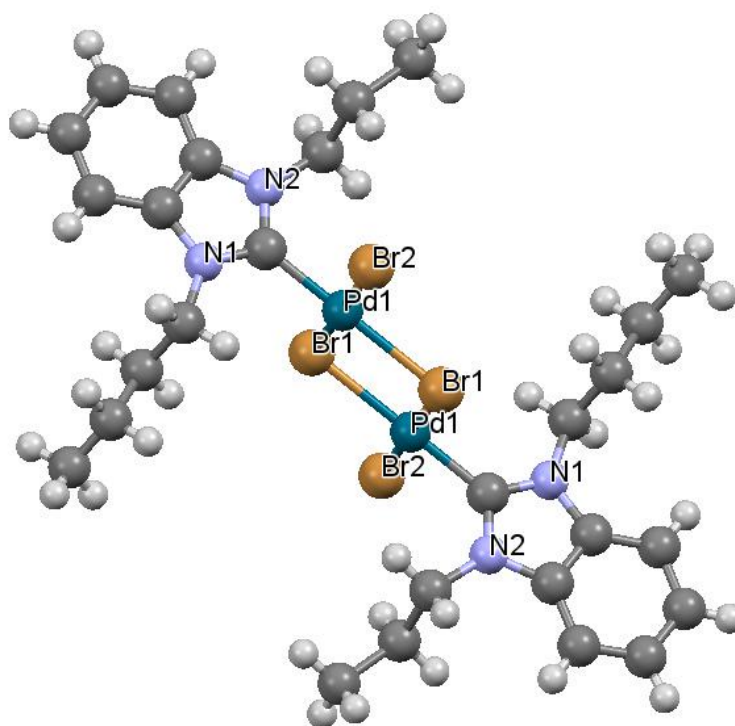


Figure-II.3: Ball and Stick representation of catalyst-A.

II.E.3b. Important crystal data of catalyst B

Empirical formula	C ₂₈ H ₄₀ Br ₂ N ₄ Pd ₁
Formula Weight	698.84

Temperature	293K
Wavelength	0.71073
Crystal system	Monoclinic
Bond precision(C-C)	0.0207 Å
Space group	P 21/c
Hall group	- P 2ybc
Unit cell dimension	a = 8.5955(6) Å $\alpha = 90$ b = 19.3454(13) Å $\beta = 109.055(4)$ c = 9.7561(8) Å $\gamma = 90$
Volume	Calculated = 1533.4(2) Å ³ Reported = 1533.39(19) Å ³
Density	1.514 g/cm ³
Z	2
Absorption coefficient	3.233 mm ⁻¹
F(000)	704.0
Completeness to theta = 30.56°	98.9%
Max. And min. Transmission	0.460 and 0.325
Correction method	Empirical
R(reflections)/wR2(reflections)	0.0725(1752)/0.2438(4647)

The crystal data of catalyst B has deposited at Cambridge Crystallographic Data Centre. The CCDC reference number is **871898**.

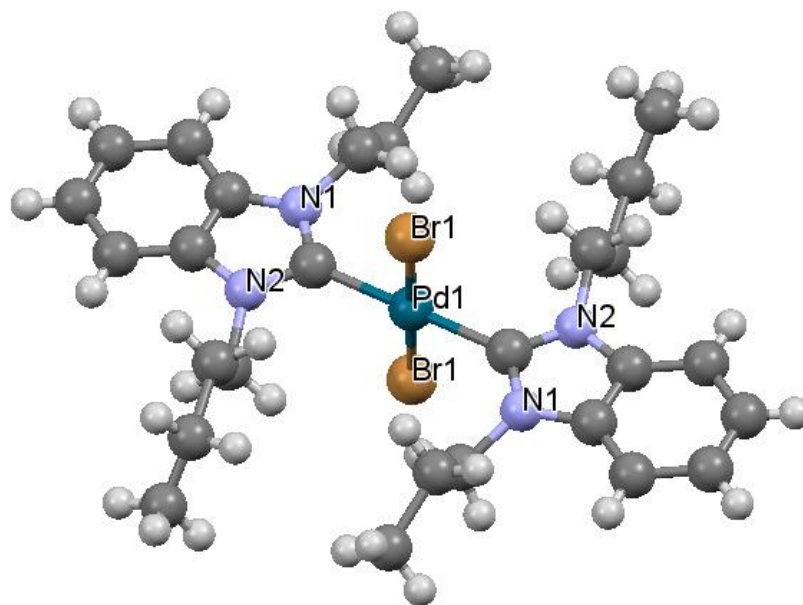


Figure-II.4: Ball and Stick representation of catalyst-B.

II.E.4. General procedure of suzuki reaction

A mixture of aryl halide (1 mmol), aryl boronic acid (1.1 mmol), catalyst-A (1 mol %, 0.0096 g), K_2CO_3 (2 mmol) and acetone/water (1:1) 3 mL were taken in 25 mL round bottom flask and the mixture was stirred at room temperature (40 °C for heteroaryl halides) until the completion of reaction. The reaction mixture was then diluted with water (20 mL) and extracted three times with dichloromethane (3 x 10 mL). The combined organic layer was washed with brine (20 mL) and dried over anhydrous Na_2SO_4 . After that it was concentrated under reduced pressure and the crude product was purified by column chromatography on silica gel (60-120 mesh) using petroleum ether (60-80 °C) and ethyl acetate were as the eluent.

II.E.5. Spectral analysis of Suzuki coupled products

Biphenyl²⁰ (Table-3, Entry-1): Isolated as white solid; 1H NMR (300 MHz, $CDCl_3$) δ 7.66-7.70(m, 4H), 7.49-7.56 (m, 4H), 7.40-7.46 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.3, 128.8, 127.3, 127.2.

4-Methylbiphenyl²¹ (Table-3, Entry-2): Isolated as white solid; 1H NMR (300 MHz, $CDCl_3$) δ 7.24-7.58 (m, 9H), 2.39 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.2, 138.3, 137.0, 129.5, 128.7, 127.2, 127.0, 126.8, 21.1.

4-Methoxybiphenyl²² (Table-3, Entry-3): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 7.54-7.59 (m, 4H), 7.42-7.47 (m, 2H), 7.27-7.35 (m, 1H), 7.00 (d, 2H, *J* = 2.4Hz), 3.87 (s, 1H); ¹³C NMR (75 MHz, CDCl₃) δ 159.1, 140.8, 133.8, 128.7, 128.2, 126.7, 126.66, 114.2, 55.3.

2-Methylbiphenyl²² (Table-3, Entry-4): Isolated as colorless oil; ¹H NMR (300 MHz, CDCl₃) δ 7.46-7.57 (m, 5H), 7.38-7.45 (m, 4H), 2.42 (s, 1H); ¹³C NMR (75MHz, CDCl₃) δ 142.1, 141.4, 135.5, 130.5, 129.9, 129.3, 128.2, 127.4, 126.9, 125.9, 20.6.

3-Methylbiphenyl²³ (Table-3, Entry-5): Isolated as colorless oil; ¹H NMR (300 MHz, CDCl₃) δ 7.69 (d, *J* = 8.7 Hz, 2H), 7.52 (m, 4H), 7.43 (m, 2H), 7.26(d, *J* = 7.2Hz, 1H), 2.59 (s, 3H); ¹³C NMR (75MHz, CDCl₃) δ 141.5, 141.3, 138.4, 128.9, 128.80, 128.78, 128.2, 128.1, 127.3, 124.4, 21.6.

2-Fluorobiphenyl²⁴ (Table-3, Entry-6): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 7.15-7.57 (m, 9H); ¹³C NMR (75MHz, CDCl₃) δ 159.8 (*J*_{CF} = 246 Hz, CF), 135.8 (C₆H₅), 130.8 (*J*_{CF} = 3.6 Hz, CH), 129.2(C₆H₅), 129.0 (*J*_{CF} = 3 Hz, CH), 128.9 (C₆H₅), 128.7 (C₆H₅), 128.4 (C₆H₅), 127.4 (*J*_{CF} = 36 Hz, C₆H₅F), 124.3 (*J*_{CF} = 3.6 Hz, CH), 116.1 (*J*_{CF} = 22.5 Hz, CH).

3-Chlorobiphenyl²⁵ (Table-3, Entry-7): Isolated as colorless oil; ¹H NMR (300 MHz, CDCl₃) δ 7.59-7.65 (m, 3H), 7.35-7.53(m, 6H); ¹³C NMR (75MHz,CDCl₃) δ 143.1, 139.8, 134.7, 130.1, 129.0, 128.0, 127.4, 127.3, 127.2, 125.4.

4-Aminobiphenyl²⁶ (Table-3, Entry-8): Isolated as pale yellow solid, ¹H NMR (300 MHz, DMSO-d₆) δ 7.43-7.46 (m, 2H), 7.27-7.31(m, 4H), 7.09-7.14 (m, 1H), 6.59-6.53(m, 2H), 5.15 (s, 1H); ¹³C NMR (75MHz, DMSO-d₆) δ 148.8, 141.2, 129.1, 128.00, 127.7, 126.1, 125.8, 114.8.

4-Acetylbiphenyl²⁴ (Table-3, Entry-9): Isolated as white solid; ¹H NMR (300MHz, CDCl₃) δ 8.03(d, *J* = 8.4 Hz, 2H), 7.61-7.69 (m, 4H), 7.45 (m, 3H), 2.63 (s, 1H); ¹³C NMR (75 MHz, CDCl₃) δ 197.8, 145.7, 139.8, 135.8, 128.92, 128.89, 128.20, 127.24, 127.19, 26.6.

3, 3'-Dimethylbiphenyl²⁷ (Table-3, Entry-14): Isolated as colorless oil, ¹H NMR (300 MHz, CDCl₃) δ 7.40-7.48 (m, 6H), 7.23 (d, *J* = 7.2, 2H), 2.50 (s, 6H); ¹³C NMR (75 MHz, CDCl₃) δ 141.4, 138.3, 128.9, 128.0, 127.98, 124.3, 21.6.

4-Cyano-4'-formylbiphenyl²⁸ (Table-3, Entry-15): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 10.02 (s, 1H), 7.99 (d, *J* = 7.8 Hz, 2H), 7.72-7.79 (m, 6H); ¹³C NMR (75 MHz, CDCl₃) δ 191.7, 144.9, 144.1, 136.1, 132.8, 130.5, 128.1, 127.9, 118.6, 112.1.

3-Phenylpyridine²⁹ (Table-4, Entry-1): Isolated as yellowish oil; ¹H NMR (300 MHz, CDCl₃) δ 8.85 (d, *J* = 2.4 Hz, 1H), 8.58 (dd, *J* = 4.8 Hz, 1.5 Hz), 7.86 (m, 1H), 7.55-7.58 (m, 3H), 7.32-7.49 (m, 3H); ¹³C NMR (75 MHz, CDCl₃) δ 148.4, 148.3, 137.8, 136.7, 134.4, 129.1, 128.1, 127.2, 123.6.

3-Phenylquinoline³⁰ (Table-4, Entry-2): Isolated as yellowish oil; ¹H NMR (300 MHz, CDCl₃) δ 9.17 (s, 1H), 8.25 (m, 1H), 8.14 (d, *J* = 8.4 Hz, 1H), 7.82 (d, *J* = 8.1 Hz, 1H), 7.66-7.71 (m, 3H), 7.49-7.56 (m, 3H), 7.38-7.47 (m, 1H); ¹³C NMR (75 MHz, CDCl₃) δ 149.9, 147.3, 137.8, 136.0, 133.8, 133.2, 129.4, 129.2, 128.1, 128.0, 127.8, 127.4, 127.0.

5-Phenylpyrimidine³¹ (Table-4, Entry-3): Isolated as colorless oil; ¹H NMR (300 MHz, CDCl₃) δ 9.18 (s, 1H), 8.93 (s, 2H), 7.44-7.58 (m, 5H); ¹³C NMR (75 MHz, CDCl₃) δ 157.4, 154.1, 134.4, 134.1, 129.5, 129.1, 127.0.

3-(4-Fluoro-phenyl)-quinoline³⁰ (Table-4, Entry-4): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 9.16 (d, *J* = 2.1, 1H), 8.33 (d, *J* = 2.1, 1H), 8.21 (d, *J* = 8.4, 1H), 7.71-7.80 (m, 1H), 7.60-7.71 (m, 4H), 7.23-7.28 (m, 2H); ¹³C NMR (75 MHz, CDCl₃) δ 164.7, 161.4, 149.0 (*J*_{CF} = 3.3Hz), 146.5, 134.1, 133.7 (*J*_{CF} = 7.4Hz), 133.4, 133.0, 129.9, 129.5, 129.1 (*J*_{CF} = 8Hz), 128.7, 128.0 (*J*_{CF} = 3.9Hz), 127.2 (*J*_{CF} = 26.70Hz), 116.3 (*J*_{CF} = 21.5Hz).

3-(3-Methyl-phenyl)-pyridine²⁹ (Table-4, Entry-5): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 8.89 (d, *J* = 1.5 Hz, 1H), 8.62 (dd, *J* = 5.1, 1.5, 1H), 7.90-7.91 (m, 1H), 7.83-7.87 (m, 1H), 7.17-7.36 (m, 4H), 2.36 (s, 3H).

1,3-Diphenylbenzene³² (Table-5, Entry-1): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 7.81 (m, 1H), 7.65 (dd, *J* = 8.4, 1.5, 4H), 7.55-7.61 (m, 2H), 7.54 (t, 1H), 7.46-7.49 (m, 3H), 7.44 (t, 1H), 7.35-7.40 (m, 2H); ¹³C NMR (75 MHz, CDCl₃) δ 141.8, 141.2, 129.2, 128.8, 127.4, 127.3, 126.2, 126.1.

1,2-Diphenylbenzene³² (Table-5, Entry-2): Isolated as pale yellow solid; ¹H NMR (300 MHz, CDCl₃) δ 7.39-7.42 (m, 6H), 7.14-7.21 (m, 8H); ¹³C NMR (75 MHz, CDCl₃) δ 141.5, 140.6, 130.6, 129.9, 127.8, 127.4, 126.42.

1,4-Diphenylbenzene³² (Table-5, Entry-3): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 7.66-7.70 (m, 8H), 7.49 (t, *J* = 7.2 Hz, 4H), 7.27-7.38 (m, 2H) ¹³C NMR (75 MHz, CDCl₃) δ 140.7, 140.1, 128.8, 127.5, 127.3, 127.0.

2,4,6-Triphenylphenol³² (Table-5, Entry-4): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 7.63-7.66 (m, 8H), 7.42-7.58 (m, 6H), 7.32-7.37 (m, 3H), 5.48 (s, 1H); ¹³C NMR (75 MHz, CDCl₃) δ 148.9, 140.5, 137.6, 133.8, 129.4, 129.1, 128.9, 128.8, 128.6, 127.8, 126.9, 126.8.

2,4,6-Triphenylaniline³³ (Table-5, Entry-5): Isolated as pale yellow solid; ¹H NMR (300 MHz, CDCl₃) δ 7.23-7.7.60 (m, 8H); ¹³C NMR (75 MHz, CDCl₃) δ 140.9, 140.3, 139.7, 131.1, 129.4, 128.9, 128.7, 128.4, 128.3, 127.4, 126.4, 126.39.

2,6-Diphenylpyridine³⁴ (Table-5, Entry-6): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 8.22-8.27 (m, 4H), 7.81 (m, 1H), 7.70 (d, 2H), 7.48-7.59 (m, 6H); ¹³C NMR (75 MHz, CDCl₃) δ 156.9, 139.5, 137.5, 129.0, 128.7, 127.0, 118.6.

II.E.6. General procedure for unsymmetrical ketone synthesis

Catalyst A (18 mg, 2 mol %), K₂CO₃ (276 mg, 2 mmol), and 3 mL of ethanol/water (1:1) were taken in a 25 mL round bottom flask and then benzoyl chloride (1.2 mmol) and arylboronic acid (1 mmol) were introduced into it. The mixture was immersed in a preheated oil bath at 50 °C for requisite reaction time as given in Scheme 1. After completion of reaction, 20 mL of water was added to it and the mixture was extracted with diethyl ether (3 x 10 mL). The combined organic layer was dried over anhydrous Na₂SO₄ and concentrated under reduced pressure. Finally the crude product was purified by column chromatography using silica gel.

II.E.7. Spectral analysis of aryl ketones

Benzophenone³⁵ (Table-6, Entry-1): Isolated as white solid; ¹H NMR (300 MHz, CDCl₃) δ 7.72-7.68(m, 4H), 7.51-7.45 (m, 2H), 7.40-7.35 (m, 4H); ¹³C NMR (75 MHz, CDCl₃) δ 195.7, 136.5, 131.4, 129.0, 127.2

Bis (4-fluorophenyl)methanone (Table-6, Entry-2): Isolated as white solid; observed melting point 107 °C-109 °C; ¹H NMR (300 MHz, CDCl₃) δ 7.79-7.84(m, 4H), 7.14-7.20 (m, 4H); ¹³CNMR (75 MHz, CDCl₃) δ 193.9, 167.1, 163.7, 133.7, 132.8, 132.6, 132.5, 115.7, 115.4; HRMS(EI+) calcd for C₁₃H₈F₂O [M]⁺ 218.0543, found 218.0547.

(2-Chlorophenyl)-phenyl-methanone (Table-6, Entry-3): Isolated as colorless oil; ^1H NMR (300 MHz, CDCl_3) δ 7.83-7.85 (d, $J = 7.8$ Hz, 2H), 7.60-7.65 (t, $J = 7.5$ Hz, 1H), 7.46-7.51 (m, 4H), 7.38-7.44 (m, 2H); ^{13}C NMR (75 MHz, CDCl_3) δ 195.4, 138.5, 136.4, 133.7, 131.3, 131.1, 130.2, 130.1, 129.1, 128.6, 126.7. HRMS(EI+) calcd for $\text{C}_{13}\text{H}_9\text{ClO}$ $[\text{M}]^+$ 216.0342, found 216.0331.

(4-Fluorobiphenyl)-(4-Fluorophenyl)-methanone (Product of scheme-2): Isolated as white solid; observed melting point 143 °C-145 °C; ^1H NMR (300 MHz, CDCl_3) δ 7.75-7.81 (m, 4H), 7.49-7.58 (m, 4H), 7.057.11 (m, 4H); ^{13}C NMR (75 MHz, CDCl_3) δ 194.8, 167.1, 164.6, 163.7, 161.4, 144.3, 136.1, 136.0, 133.8, 132.7, 132.6, 131.0, 130.6, 130.2, 129.0, 128.9, 126.9, 116.1, 115.8, 115.7, 115.4. HRMS(EI+) calcd for $\text{C}_{19}\text{H}_{12}\text{F}_2\text{O}$ $[\text{M}]^+$ 294.0856, found 294.0859.

II.F. References

1. (a) Hassan, J.; Sevignon, M.; Gozzi, C.; Schulz, E.; Lemaire, M. *Chem. Rev.* **2002**, *102*, 1359; (b) Miyaura, N. *Top. Curr. Chem.* **2002**, *219*, 11; (c) Shin, J. Y.; Lee, B. S.; Jung, Y.; Kim, S. J.; Lee, S. *Chem. Commun.* **2007**, 5238; (d) Doucet, H. *Eur. J. Org. Chem.* **2008**, 2013; (e) Budarin, V. L.; Clark, J. H.; Luque, R.; Macquarrie, D. J.; White, R. J. *Green Chem.* **2008**, *10*, 382; (f) Kotha, S.; Lahiri, K.; Kashinath, D. *Tetrahedron*, **2002**, *58*, 9633.
2. a) Arduengo, A. J.; Harlow, R. L.; Kline, M. *J. Am. Chem. Soc.* **1991**, *113*, 361; (b) Arduengo, A. J. *Acc. Chem. Res.* **1999**, *32*, 913; (c) Bourissou, D.; Guerret, O.; Gabbai, F. P.; Bertrand, G. *Chem. Rev.* **2000**, *100*, 39; (d) Fortman, G. C.; Nolan, S. P. *Chem. Soc. Rev.* **2011**, *40*, 5151; (e) Moore, J. L.; Rovis, T. *Top. Curr. Chem.* **2010**, *291*, 77; (f) Valente, C.; Calimsiz, S.; Hoi, K. H.; Mallik, D.; Sayah, M.; Organ, M. G. *Angew. Chem. Int. Ed.* **2012**, *51*, 3314.
3. (a) Biju, A. T.; Kuhl, N.; Glorius, F. *Acc. Chem. Res.* **2011**, *44*, 1182; (b) Marion, N.; Gonzalez, S. D.; Nolan, S. P. *Angew. Chem. Int. Ed.* **2007**, *46*, 2988; (c) Nair, V.; Vellalath, S.; Babu, B. P. *Chem. Soc. Rev.* **2008**, *37*, 2691; (d) Bugaut, X.; Glorius, F. *Chem. Soc. Rev.* **2012**, *41*, 3511; (e) Nair, V.; Menon, R. S.; Biju, A. T.; Sinu, C. R.; Paul, R. R.; Jose, A.; Sreekumar, V. *Chem. Soc. Rev.* **2011**, *40*, 5336.
4. (a) González, S. D.; Nolan, S. P. *Top. Organomet. Chem.* **2007**, *21*, 47; (b) Marion, N.; Navarro, O.; Mei, J.; Stevens, E. D.; Scott, N. M.; Nolan, S. P. *J. Am. Chem. Soc.* **2006**, *128*, 4101; (c) Sreenivasulu, M.; Kumar, K. S.; Kumar, P. R.; Chandrasekhar, K. B.; Pal, M. *Org. Biomol. Chem.* **2012**, *10*, 1670; (d) Yigit, B. *Transition Met. Chem.* **2012**, *37*, 183; (e) Gonzalez, S. D.; Marion, N.; Nolan, S. P. *Chem. Rev.* **2009**, *109*, 3612.
5. Gstottmayr, C. W. K.; Bohm, V. P. W.; Herdtweck, E.; Grosche, M.; Herrmann, W. A. *Angew. Chem. Int. Ed.*, **2002**, *41*, 1363.
6. (a) Sau, S. C.; Santra, S.; Sen, T. K.; Mandal, S. K.; Koley, D. *Chem. Commun.* **2012**, 48, 555; (b) Tu, T.; Fang, W.; Jiang, J. *Chem. Commun.* **2011**, 47, 12358; (c) Navarro, O.; Kelly, R. A.; Nolan, S. P. *J. Am. Chem. Soc.* **2003**, *125*, 16194.
7. (a) Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Angew. Chem. Int. Ed.* **2007**, *46*, 2768; (b) Viciu, M. S.; Navarro, O.; Germaneau, R. F.; Kelly, R. A.; Sommer, W.;

- Marion, N.; Stevens, E. D.; Cavallo, L.; Nolan, S. P. *Organometallics*, **2004**, *23*, 1629.
8. (a) Bohm, V. P. W.; Gstottmayr, C. W. K.; Weskamp, T.; Herrmann, W. A. *J. Organomet. Chem.* **2000**, *595*, 186; (b) Navarro, O.; Kaur, H.; Mahjoor, P.; Nolan, S. P. *J. Org. Chem.* **2004**, *69*, 3173.
9. (a) Cavallo, L.; Correa, A.; Costabile, C.; Jacobsen, H. *J. Organomet. Chem.* **2005**, *690*, 5407; (b) O. Köhl, *Coord. Chem. Rev.* **2009**, *253*, 2481.
10. (a) Xu, L.; Chen, W.; Xiao, J. *Organometallics*, **2000**, *19*, 1123; (b) McLachlan, F.; Mathews, C. J.; Smith, P. J.; Welton, T. *Organometallics*, **2003**, *22*, 5350; (c) Mathews, C. J.; Smith, P. J.; Welton, T.; White, A. J. P.; Williams, D. J. *Organometallics*, **2001**, *20*, 3848.
11. De Kimpe, N.; Keppens, M.; Froncg, G. *Chem. Commun.* **1996**, 635.
12. (a) Gmouh, S.; Yang, H.; Vaultier, M. *Org. Lett.* **2003**, *5*, 2219. (b) Fillion, E.; Fishlock, D.; Wilsily, A.; Goll, J. M. *J. Org. Chem.* **2005**, *70*, 1316.
13. (a) Sumino, S.; Ui, T.; Ryn, I. *Org. Lett.* **2013**, *15*, 3142; (b) Ishiyama, T.; Kizaki, H.; Hayashi, T.; Suzuki, A.; Miyaura, N. *J. Org. Chem.* **1998**, *63*, 4726; (c) Tambade, P. J.; Patil, Y. P.; Panda, A. G.; Bhanage, B. M. *Eur. J. Org. Chem.* **2009**, 3022.
14. Xin, B.; Zhang, Y.; Cheng, K. *J. Org. Chem.* **2006**, *71*, 5725.
15. (a) Lin, X.-F.; Li, Y.; Li, S.-Y.; Xiao, Z.-K.; Lu, J.-M. *Tetrahedron*, **2012**, *68*, 5806; (b) Ogawa, D.; Hyodo, K.; Suetsugu, M.; Li, J.; Inoue, Y.; Fujisawa, M.; Iwasaki, M.; Takagi, K.; Nishihara, Y. *Tetrahedron*, **2013**, *69*, 2565; (c) Ekoue-Kovi, K.; Xu, H.; Wolf, C. *Tetrahedron Lett.* **2008**, *49*, 5773.
16. (a) Hadei, N.; Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Org. Lett.* **2005**, *7*, 1991; (b) O'Brien, C. J.; Kantchev, E. A. B.; Chass, G. A.; Hadei, N.; Hopkinson, A. C.; Organ, M. G.; Setiadi, D. H.; Tange, T. H.; Fang, D. C. *Tetrahedron* **2005**, *61*, 9723; (c) Liu, Z.; Gu, P.; Shi, M.; McDowell, P.; Li, G. *Org. Lett.* **2011**, *13*, 2314; (d) Jackstell, R.; Frisch, A.; Beller, M.; Röttger, D.; Malaun, M.; Bildstei, B. *J. Mol. Catal. A: Chem.* **2002**, *185*, 105.
17. (a) Huynh, H. V.; Ho, J. H. H.; Neo, T. C.; Koh, L. L. *J. Organomet. Chem.* **2005**, *690*, 3854; (b) Metallinos, C.; Barrett, F. B.; Chaytor, J. L.; Heska, M. E. A. *Org. Lett.* **2004**, *6*, 3641.
18. Gupta, S.; Chatterjee, A.; Das, B.; Das, S.; Basu, B. *J. Chem. Eng. Data.* **2013**, *58*, 1.
19. Zhang, L.; Wu, J.; Shi, L.; Xia, C.; Li, F. *Tetrahedron Lett.* **2011**, *52*, 3897.

20. Klingensmith, L. M.; Leadbeater, N. E. *Tetrahedron Lett.* **2003**, *44*, 765.
21. Yang, W.; C. Liu, C.; Qui, J. *Chem. Commun.* **2010**, *46*, 2659.
22. Schmidt, A.; Rahimi, A. *Chem. Commun.* **2010**, *46*, 2995.
23. Shi, S.; Zhang, Y. *J. Org. Chem.*, **2007**, *72*, 5927.
24. Liang, L. C.; Chien, P. S.; Huang, M. H. *Organometallics* **2005**, *24*, 353.
25. Mahamo, T.; Mogorosi, M. M.; Moss, J. R.; Mapolie, S. F.; Slootweg, J.; Lammertsma, K.; Smith, G. S. *J. Organomet. Chem.*, **2012**, *703*, 34.
26. Rao, G. K.; Kumar, A.; Kumar, B.; Singh, A. K. *Dalton Trans.* **2012**, *41*, 4306.
27. Gadda, T. M.; Kawanishi, Y.; Miyazawa, A. *Synth. Commun.* **2012**, *42*, 1259.
28. Ismail, M. A.; Batista-Parra, A.; Miao, Y.; Wilson, W. D.; Wenzler, T.; Brun, R.; Boykina, D. W. *Bioorg. Med. Chem.* **2005**, *13*, 6718.
29. Ye, M.; Gao, G.-L.; Edmunds, A. J. F.; Worthington, P. A.; Morris, J. A.; Yu, J.-Q. *J. Am. Chem. Soc.* **2011**, *133*, 19090.
30. Zhang, Y.; Wang, M.; Li, P.; Wang, L. *Org. Lett.* **2012**, *14*, 2206.
31. Zhao, Y.; Zhou, Y.; Ma, D.; Liu, J.; Li, L.; Zhang, T. Y.; Zhang, H. *Org. Biomol. Chem.* **2003**, *1*, 1643.
32. Liu, L.; Zhang, Y.; Xin, B. *J. Org. Chem.* **2006**, *71*, 3994.
33. Basu, B.; Das, S.; Kundu, S.; Mandal, B. *Synlett*, **2008**, *2*, 255.
34. Dong, C. G.; Hu, Q. S. *J. Am. Chem. Soc.* **2005**, *127*, 10006.
35. Urawa, Y.; Ogura, K. *Tetrahedron Lett.* **2003**, *44*, 271.