Primary amine-based palladium(II) complexes as catalysts for Suzuki-Miyaura reaction: Experimental and theoretical investigations on the effects of substituents on nitrogen atom

Archana Tairai[a], Pradip K Bhattacharyya [b], Rahul Kar[a] & Pankaj Das[a, c, *]

[a]Department of Chemistry, Dibrugarh University, Dibrugarh 786 004, Assam, India
Email: pankajd29@yahoo.com

[b]Department of Chemistry, Arya Vidyapeeth College, Guwahati 781 016, Assam, India
[c]Department of Chemistry, Rajiv Gandhi University, Doimukh, Rono Hills, Itanagar 791 112, Arunachal Pradesh, India

Catalytic efficiencies of eight primary amine-based palladium(II) complexes of general formula, *trans*-[PdCl$_2$(RNH$_2$)$_2$] (**1L$_1$-L$_8$**), have been evaluated for the Suzuki-Miyaura reaction of 4-bromonitrobenzene with phenylboronic acid at room temperature in water. The efficiencies of the catalysts follow the order: Ph$_3$CNH$_2$ (**L$_8$**) > Ph$_2$CHNH$_2$ (**L$_7$**) > Ph$_2$CH$_2$NH$_2$ (**L$_6$**) > ^{t}BuNH$_2$ (**L$_4$**) > CyNH$_2$ (**L$_5$**) > ^{i}PrNH$_2$ (**L$_2$**) > ^{n}BuNH$_2$ (**L$_3$**) > ^{n}PrNH$_2$ (**L$_1$**). In order to ascertain the parameters affecting catalytic efficiencies, DFT based reactivity descriptors have been analyzed for the ligands. Good linear correlation is obtained between the observed yield (%) and the gas phase reactivity descriptors (chemical hardness, chemical potential and electrophilicity index). Good-to-excellent yields of coupling products are achieved using the **1L$_8$** complex as the catalyst for a range of aryl halides.

Keywords: Density functional calculations, Catalysts, Suzuki-Miyaura reactions, Cross coupling reactions, Palladium, Amine-based ligands

The palladium-catalyzed Suzuki-Miyaura cross-coupling reactions of aryl halides with arylboronic acids has proven to be one of the most powerful strategies for synthesizing diversified biaryls, which constitute an important class of compounds for pharmaceutical, material and agricultural chemistry[1,2]. It is well known that in transition metal-based homogeneous catalysis the activity and selectivity of a catalyst depends on the steric and electronic properties of the ligands attached to the metal. Thus, right choices of ligands play a crucial role in such catalysis. Amongst the various ligands, phosphine-based ligands were found to be the most popular choice for Suzuki-Miyaura reactions[3-13]. It may be important to mention that the phosphine ligands are generally toxic, air and moisture sensitive and often require an inert atmosphere which causes significant inconvenience in handling. Consequently, attempts have been made to employ different N-donor ligands in Suzuki-Miyaura reaction because of their low toxicity and/or easy-to-handle property. Remarkable success have been achieved with N-containing ligands such as N-heterocyclic carbenes[14-18], palladacycles[19-21], oximes[22-24], etc. Surprisingly, Suzuki-Miyaura reactions employing simple amines as ligands have got relatively less attention. Although there exist a few reports on the use of amine-based ligands in Suzuki-reactions[25-28], majority of such amines are secondary or tertiary. On the contrary, primary amines as ligands remained largely unexplored in Suzuki-Miyaura reactions, even though a large number of such amines are commercially available and are very cheap. Boykin *et al.*[26] screened a series of commercially available amines including some primary amines, for the Suzuki-Miyaura reactions and observed that sterically bulky primary amines appeared to be better ligands than comparable bulky tertiary amines. Recently, we have developed an *in situ* catalytic system based on primary amine-based ligands and PdCl$_2$, wherein the catalytic species generated in the reaction mixture itself effectively catalyzed the Suzuki-Miyaura reaction between aryl bromides with arylboronic acids at room temperature[29]. Herein, we extend our work by exploring the catalytic potential of eight primary amine-based palladium complexes in the Suzuki-Miyaura reactions. The syntheses and structural characterizations of some of the complexes have been reported in literature[30-34].

It is expected that different groups attached to the nitrogen atom of the amine-based ligands will influence the catalytic result. Thus, in order to draw a relationship between the observed catalytic trend with properties of ligands, we have computed some DFT-based reactivity descriptors such as chemical potential, chemical hardness and electrophilicity index of the ligands. These descriptors generally describe the stability and reactivity of a system and applicability of such descriptors have been tested for a wide range of systems[35,36]. Thus, it was thought of interest to investigate these DFT-based reactivity descriptors to understand the performance of the amine-based ligands for palladium catalyzed Suzuki-Miyaura reactions.

Materials and Methods

PdCl$_2$, *n*-propylamine (**L$_1$**), *iso*-propylamine (**L$_2$**), *n*-butylamine (**L$_3$**), *tert*-butylamine (**L$_4$**) and benzylamine (**L$_6$**) were purchased from Loba Chemie. Triphenylmethylamine (**L$_8$**) and cyclohexylamine (**L$_5$**) were purchased from Fluka, while diphenylmethanamine (**L$_7$**) was purchased from Aldrich. The solvents used were of analytical grade and distilled prior to utilization. Elemental analyses were recorded on a Elementar Vario EL III Carlo Erba 1108 analyzer. IR spectra (4000-250 cm^{-1}) were recorded in KBr on a Shimadzu (Prestige-21) spectrometer. The ^{1}H NMR spectra were recorded in CDCl$_3$ on a Bruker Avance II 400 MHz spectrometer operating at 400.13 MHz. The ESI-mass spectra of the complexes were recorded on a Waters ZQ-4000 mass spectrometer. The melting points were determined by Buchi B450 melting point apparatus.

General procedure for synthesis of complexes

A solution of the appropriate ligand RNH$_2$ (1.13 mmol) in 20 mL acetonitrile was added dropwise to a solution of PdCl$_2$ (0.56 mmol) in 10 mL of acetonitrile. The resultant solution was refluxed for 3 h. A yellow/yellowish brown colored compound precipitated. After filtration and washing the residue with acetonitrile, the complexes isolated as yellow or yellow-brown solid. Charaterisation data are given below:

trans-[PdCl$_2$(^{i}PrNH$_2$)$_2$] (**1L$_2$**): Colour: Bright yellow; Yield: 86 %; Anal. (%): Calc. for C$_6$H$_{18}$Cl$_2$N$_2$Pd: C, 24.38; H, 6.14; N, 9.48. Found: C, 24.09; H, 6.11; N, 9.51 MS-ESI: *m/z* = 260.6 (20 %) [M-Cl]$^+$, 222.7 (100 %) [M-2Cl-2]$^+$; IR (KBr, cm^{-1}): ν$_{N-H}$: 3259.7, 3219.2; ν$_{Pd-N}$: 437.8, ν$_{Pd-Cl}$: 342.0;

^{1}H NMR (CDCl$_3$), 3.29 (h, 2H, CH), 2.71 (br, 4H, NH$_2$), 1.36 (d, *J* = 6.8 Hz, 12H, CH$_3$).

trans-[PdCl$_2$(Ph$_2$CHNH$_2$)$_2$] (**1L$_7$**): Colour: Yellowish brown; Yield: 91 %; Anal. (%): Calc. for C$_{26}$H$_{26}$Cl$_2$N$_2$Pd: C, 57.42; H, 4.82; N, 5.15. Found: C, 57.13; H, 4.81; N, 5.13; MS-ESI: *m/z* = 507.3 (30 %) [M-Cl-1]$^+$, 470.9 (100 %) [M-2Cl-2]+; IR (KBr, cm^{-1}): ν$_{N-H}$: 3209.5, 3172.9, ν$_{Pd-N}$: 474.5; ν$_{Pd-Cl}$: 324.0; ^{1}H NMR (CDCl$_3$), 7.19-7.41 (m, 20H, Ph), 4.83 (s, 2H, CH), 3.19 (br, 4H, NH$_2$).

trans-[PdCl$_2$(Ph$_3$CNH$_2$)$_2$] (**1L$_8$**): Colour: Bright yellow; Yield: 88 %; Anal. (%): Calc. for C$_{38}$H$_{34}$Cl$_2$N$_2$Pd: C, 65.57; H, 4.92; N, 4.02. Found: C, 66.01; H, 4.94; N, 3.98; MS-ESI: *m/z* = 582.3 (20 %) [M-Ph-Cl]$^+$, 547.1 (40 %) [M-Ph-2Cl]$^+$, 363.8 (100 %) [M-Ph$_3$CNH$_2$-2Cl-1]$^+$; IR (KBr, cm^{-1}): ν$_{N-H}$: 3296.4, 3205.69, ν$_{Pd-N}$: 468.5; ν$_{Pd-Cl}$: 360.7; ^{1}H NMR (CDCl$_3$), 7.28-7.36 (m, 30H, Ph), 2.17 (br, 4H, NH$_2$).

Catalytic studies

The Suzuki-Miyaura cross-coupling reactions were carried out under aerobic condition. The progresses of the reactions were monitored by thin layer chromatography using aluminum coated TLC plates (Merck) under UV light. The products were purified by column chromatography using silica gel (60-120 mesh). The various products separated were characterized by melting point, mass spectroscopy and ^{1}H NMR spectroscopy and compared with the authentic samples.

General procedure for the Suzuki-Miyaura reactions of aryl halides

A 50 mL round bottomed flask was charged with a mixture of aryl halide (2 mmol), arylboronic acid (2.2 mmol), K$_2$CO$_3$ (6 mmol), catalyst (0.05 mol %) and water (6 mL). The mixture was stirred at room temperature for the required time. Then the mixture was diluted with water (20 mL) and extracted with ether (3 × 20 mL). The combined extract was washed with brine (3 × 20 mL) and dried over Na$_2$SO$_4$. After evaporation of the solvent under reduced pressure, the residue was chromatographed (silica gel, ethyl acetate/hexane, 1:9) to obtain the desired products.

Computational details

The structure of the eight amine ligands (**L$_1$.L$_8$**) were optimized at B3LYP/6-311++G(d,p) level of theory using Gaussian09 software[37]. The minimum energy structures of all the molecules were confirmed by zero number of imaginary frequencies. The global

reactivity descriptors such as chemical potential (μ), hardness (η) and electrophilicity index (ω) were calculated from the orbital energies of highest occupied molecular orbital (ε_{HOMO}) and lowest unoccupied molecular orbital (ε_{LUMO}) using the following equations:

$$\mu = \frac{\varepsilon_{LUMO} + \varepsilon_{HOMO}}{2}, \quad \eta = \frac{\varepsilon_{LUMO} - \varepsilon_{HOMO}}{2} \quad \text{and} \quad \omega = \frac{\mu^2}{2\eta}.$$

The frontier molecular orbitals were generated in Gaussview.

Results and Discussion

Eight palladium complexes of general formula *trans*-[PdCl$_2$(RNH$_2$)$_2$] (**1**) (R = *n*-propyl (**L$_1$**); *iso*-propyl (**L$_2$**); *n*-butyl (**L$_3$**); *tert*-butyl (**L$_4$**); cyclohexyl (**L$_5$**); benzyl (**L$_6$**); diphenylmethyl (**L$_7$**); triphenylmethyl (**L$_8$**)) were screened as pre-catalysts for the Suzuki-Miyaura cross-coupling reactions. The palladium complexes were synthesized by following the literature method of preparation[38]. The complexes **1L$_1$**, **1L$_3$-1L$_6$** are already reported[39,31-34] and their identities confirmed by mass spectral and NMR data. The complexes, **1L$_7$** and **1L$_8$**, are newly synthesized and completely characterized by ESI-mass, elemental analyses and IR and ^{1}H NMR spectroscopy. Although **1L$_2$** has been reported previously[30], except elemental analysis no characterization data is available. Hence, **1L2** has been characterized herein by ESI-mass, IR and ^{1}H NMR spectroscopy. Literature survey reveals that there exists one report where ligand **L$_8$** was used

to form complex with palladium[40], but to the best of our knowledge the ligand **L$_7$** has not been used so far to form palladium complex.

Catalytic efficiency of amine-based complexes for Suzuki-Miyaura reactions

In order to investigate the efficiencies of the complexes **1L$_1$-1L$_8$** as catalysts for Suzuki-Miyaura reaction, initial catalyst testing was performed by using 4-bromonitrobenzene and phenylboronic acid as coupling partner. All the reactions were performed in water under aerobic condition at room temperature using K$_2$CO$_3$ as base at low catalyst loading (0.001 mmol) and the results were shown in Table 1. It may be noted that from environmental and economic points of view, the use of water as a solvent in the Suzuki-Miyaura reaction is of tremendous interest because water is very cheap, readily available and non-toxic. Literature survey reveals some reports where water was successfully used as solvent in Suzuki-Miyaura reaction[41-45], although in most of the cases either a high reaction temperature or the use of phase-transfer catalyst or an organic co-solvent was necessary for maximizing catalytic performances In the present case, we used neat water as solvent without using any phase-transfer catalyst. The complex **1L$_8$** was found to be the most efficient giving 86 % yield whereas the complex **1L$_1$** was found to be the least efficient giving only 18 % yield. Table 1 reveals that the observed catalytic trend follow the order: **1L$_8$ > 1L$_7$ > 1L$_6$ > 1L$_4$ > 1L$_5$ > 1L$_2$ > 1L$_3$ > 1L$_1$**.

Table 1—Catalytic activity of palladium amine complexes for Suzuki-Miyaura cross-coupling reactions.
[React. cond.: 4-bromonitrobenzene (2.0 mmol); phenylboronic acid (2.2 mmol); K$_2$CO$_3$ (6.0 mmol); water: 6 mL]
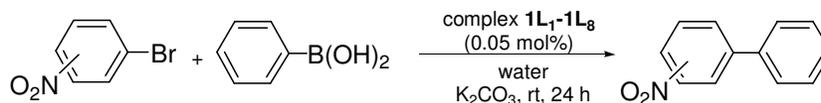
Entry	Ligand	pK_a	Cone angle	Yield (%)[f]
1	*n*-Propyl amine (**L$_1$**)	10.60[a]	106[d]	18
2	*iso*-Propylamine (**L$_2$**)	10.63[a]	106[d]	31
3	*n*-Butylamine (**L$_3$**)	10.65[a]	106[d]	21
4	*tert*-Butylamine (**L$_4$**)	10.68[a]	106[d]	52
5	Cyclohexylamine (**L$_5$**)	10.63[b]	115[d]	39
6	Benzylamine (**L$_6$**)	9.33[a]	123[d]	63
7	Diphenylmethylamine (**L$_7$**)	7.30[b]	-na[e]	72
8	Triphenylmethylamine (**L$_8$**)	9.20[c]	-na[e]	86

[a]Ref. 50; [b]Ref. 51; [c]Ref. 52; [d]Ref. 54;
[e]Literature data not available;
[g]Isolated yield (yields are of average of two runs).

Effects of steric and electronic properties of the ligand on catalytic activity

Amines are important ligands in transition metal chemistry and the steric and electronic properties of such amines in metal complexes are often important in understanding the reactivity and selectivity of various catalytic processes[46]. Generally, electronic properties of amines are related to their pK_a trends. However, comparing the available literature values of pK_a of amines[47-49] with the observed catalytic trend, no direct correlation could be made. For example, *tert*-butylamine (**L₃**) and *n*-butylamine (**L₄**) had very close pK_a values but the corresponding complexes **1L₃** and **1L₄** showed significant differences in their catalytic results (Table 1, entry 3 & 4). Likewise, *n*-propylamine (**L₁**) and *iso*-propylamine (**L₂**) had very close pK_a values but showed different catalytic results (Table 1, entry 1 & 2). It is well established that to quantify the steric effects of ligands, the cone-angle concept introduced by Tolman[50] is considered to be a widely applied concept. Although the concept was traditionally introduced for phosphine-based ligands, it also worked well with amine-based ligands. However, like pK_a, in this case also, no direct conclusion could be derived to explain the observed catalytic trend based on the available literature values of cone-angles of amines[51]. For example, ligands **L₁-L₄** have the same cone-angle but their corresponding complexes as catalysts showed significant variations in yields (Table 1, entries 1-4).

Density functional theory studies

It can be observed from Table 1 that there is no straightforward correlation between the catalytic trends and the steric or electronic properties of the amine-based ligands. We, therefore, investigated the reactivity descriptors to identify the correlation, if any, with the percentage yield of the Suzuki-Miyaura reactions. The energy of highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO), chemical hardness, chemical potential, electrophilicity index and charge density on the N-atom of the eight amine-based ligands are summarized in Table 2.

HOMO-LUMO viewpoint

Amines are a class of ligands that usually donates σ-electron density to the metal through its nitrogen atom while forming coordination complex. However, there are instances that aromatic polycyclic amines such as 2,2´-bipyridine or 1,10-phenanthroline can also use their π-antibonding orbitals as metal d-electron acceptor. It is generally accepted that HOMO of the ligand controls the electron donating ability, while LUMO gives information about the electron accepting capability. Hence, to understand the nature of donor-acceptor behavior we have observed the positions and shapes of HOMO and LUMO of all the ligands. In view of the fact that similar information is given by the orbital diagrams of aliphatic or aromatic ligands, we present the shape of HOMO and LUMO of only one aliphatic (**L₁**) and one aromatic (**L₈**) ligand in Fig. 1, while for the remaining ligands the shapes of the orbitals are shown in Fig. S1 (Supplementary Data). It has been observed that in the case of aliphatic amines (Fig. 1a), the HOMO is localized on the nitrogen atom which is in accordance with the formation of palladium-amine complex through nitrogen atom. On the other hand, it is interesting to note that in the case of aromatic amines, in addition to the nitrogen atom a significant portion of the HOMO is also localized on the aromatic ring (Fig. 1c) indicating that the ring carbons are also capable of forming a bond with the metal resulting in

Table 2—Values of $\mathcal{E}_{HOMO}$, $\mathcal{E}_{LUMO}$, chemical hardness (η), chemical potential (μ) and electrophilicity (ω) at B3LYP/6-311++G(d,p) level of theory

Ligand	$\mathcal{E}_{HOMO}$ (a. u.)	$\mathcal{E}_{LUMO}$ (a. u.)	η (a. u.)	μ (a. u.)	ω (a. u.)
L₁	-0.2421	-0.0099	0.1161	-0.1260	0.0684
L₂	-0.2424	-0.0123	0.1151	-0.1274	0.0705
L₃	-0.2418	-0.0101	0.1158	-0.1259	0.0685
L₄	-0.2429	-0.0148	0.1141	-0.1289	0.0728
L₅	-0.2380	-0.0113	0.1134	-0.1247	0.0686
L₆	-0.2423	-0.0196	0.1114	-0.1309	0.0769
L₇	-0.2424	-0.0253	0.1085	-0.1339	0.0826
L₈	-0.2398	-0.0303	0.1047	-0.1351	0.0871
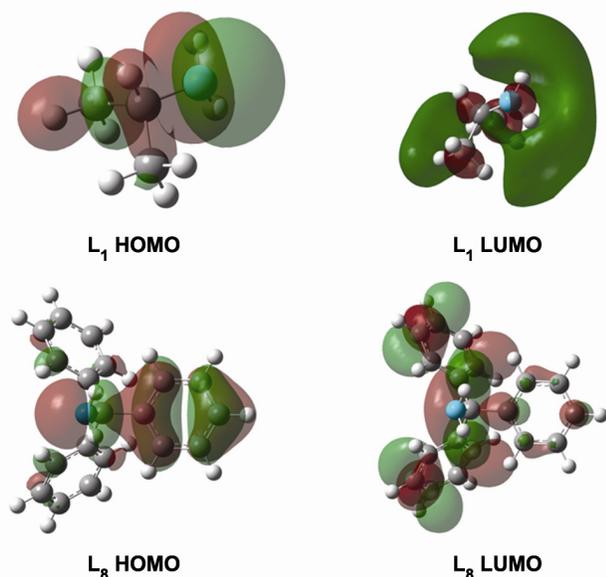
Fig. 1—Shapes of HOMO and LUMO of the ligands L_1 and L_8.

formation of a palladacycle. It may be mentioned that the palladacycle forming capacity of benzyl amine or its derivatives have been extensively investigated by Vicente *et al.*[39,52] However, in the present case (complexes $1L_6$-$1L_8$) such a possibility is remote as all the coordination sites of palladium are occupied. Interestingly, the LUMO diagram of aromatic amines (L_6-L_8) reveals that a substantial amount of LUMO is localized on the aromatic ring (Fig. 1d), suggesting that these three ligands can act as potential π-acceptors. This fact is further substantiated by the more negative values of ε_{LUMO} of the aromatic amines compared to that of aliphatic amines (Table 2). Moreover, among the aromatic amines ligand L_8 has the most negative value of ε_{LUMO} indicating that the electron accepting capacity of L_8 is maximum. It is noteworthy that phosphines are recognized as highly efficient ligands in various metal catalyzed reactions including palladium catalyzed Suzuki-Miyaura reactions and their high efficiencies are attributed to their σ-donor/π-acceptor synergism property. Thus, based on the molecular orbital diagram of ligand L_8 and its superiority in catalytic efficiency, we propose that a phosphine like synergism could be present in the complex $1L_8$.

Correlation of reactivity descriptors with catalytic activity

Conceptual DFT derives chemical concepts from the reactivity descriptors defined within the framework of density functional theory. One such reactivity descriptor is chemical hardness (η) which

represents the resistance of a system to changes in its number of electrons (*N*). Chemical hardness has been established as an electronic quantity which may be used to characterize relative stability of molecules in many cases[53]. Higher the value of η, harder is the ligand. It can be observed from Table 2 that the aliphatic amines (L_1-L_5) are much harder than the aromatic amines (L_6-L_8). Moreover, among the aromatic amines, the presence of higher number of phenyl rings at the α-carbon makes the ligand softer. For instance, the ligand L_8 possessing lowest value of η is the softest amongst the eight ligands. The order of the ligands based on their η values is: $L_8 < L_7 < L_6 < L_5 < L_4 < L_2 < L_3 < L_1$. A graph of the calculated value of η of amines with catalytic yield is shown in Fig. 2a, which reveals that with the decrease in chemical hardness of amines, the catalytic activity increases. Indeed, a good linear fit with $R^2 = 0.892$ was observed between the two parameters. The best result was obtained when η value was minimum (L_8: 86 % yield) and the least catalytic activity was found when η value was maximum (L_1: 18 % yield).

Chemical potential is another reactivity descriptor that signifies the escaping tendency of the electronic cloud and is equal to the negative value of electronegativity ($\mu = -\chi$). The ligands with one or more aromatic rings (L_6-L_8) attached to α carbon have lower values of chemical potential compared to the ligands L_1-L_5. The ligand L_8, which possesses three electron withdrawing phenyl group attached to the nitrogen atom has the lowest value (–0.1351 a.u.). In order to find a correlation between the calculated chemical potential with the observed catalytic yield, we have plotted chemical potential of the ligands against the observed yield (Fig. 2b). Figure 2b shows that catalytic activity increases with the decrease in chemical potential of amines. Similar to chemical hardness, in this case also a good linear correlation ($R^2 = 0.857$) was obtained between the two parameters.

Electrophilicity index on the other hand, measures the stabilization in energy when the system acquires an additional electronic charge ΔN from the environment. It allows a quantitative classification of the global electrophilic nature of a molecule within a relative scale. Higher the value of ω, more is the electrophilic nature. Table 2 reveals that the ligands with aromatic ring (L_6-L_8) are good electrophiles and can accept electron density in LUMO. On arranging the ligands based on their ω values, the order is: $L_8 > L_7 > L_6 > L_4 > L_5 > L_2 > L_3 > L_1$. Similar to

chemical hardness and chemical potential a direct linear correlation ($R^2 = 0.898$) was obtained between the electrophilicity of the ligand with the percentage yield (Fig. 2c).
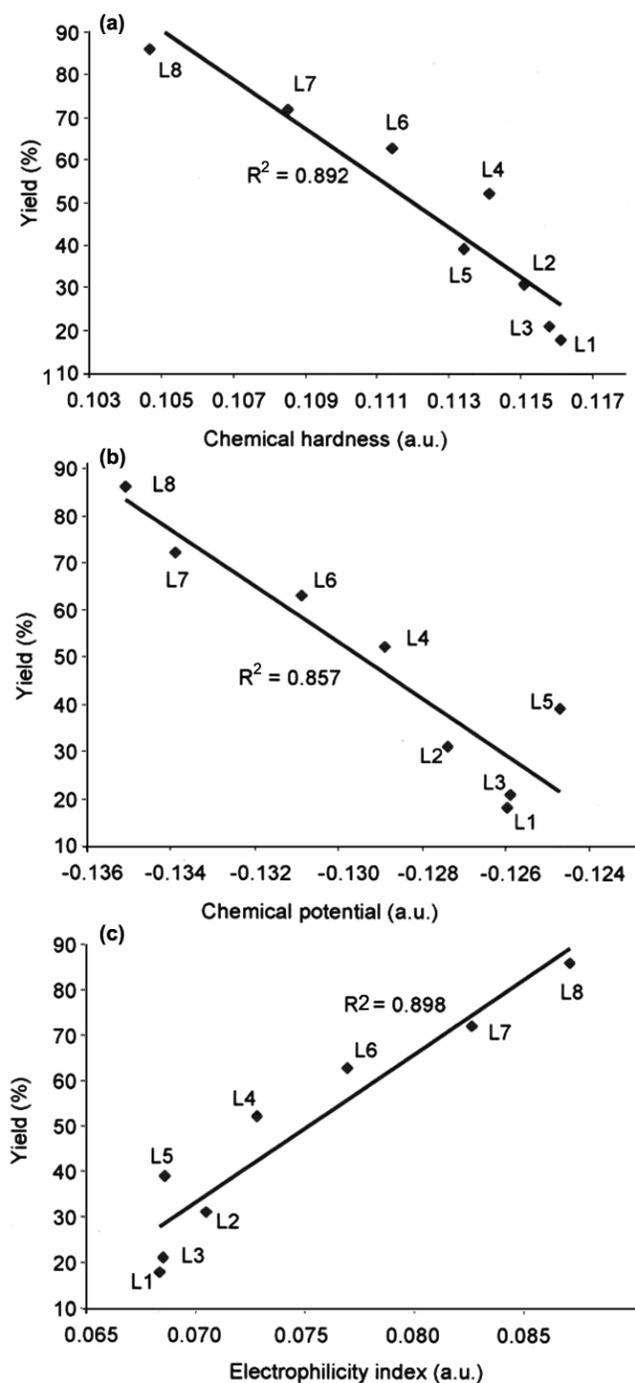
Fig. 2—Variation of yield (%) with (a) chemical hardness, (b) chemical potential, and, (c) electrophilicity index of the amine-based ligands.

Screening of different substrates using complex $1L_8$ as catalyst

It is seen from Table 1 that the complex $\mathbf{1L_8}$ is the best catalyst amongst the studied complexes under similar experimental conditions. Thus, to evaluate the effectiveness of the current catalytic system, reactions of several electronically diverse aryl halides with arylboronic acids were examined using complex $\mathbf{1L_8}$ as catalyst (Table 3). Our results show that the aryl bromides with electron-withdrawing substituents such as NO_2, CHO and CO_2Me (entries 1-5) undergo coupling reactions with phenylboronic acid and produce good-to-excellent yields of the coupling products (84-92 %). The electron-neutral and electron-donating aryl bromides (such as, bromobenzene, 4-bromotoluene and 4-bromoanisole) also gave the coupling products in good-to-excellent yields (entries 7-9). However, only moderate yields were obtained with sterically demanding substrates such as 2-bromotoluene and 2-bromoanisole (entries 10 & 11). It is important to highlight that although the electronic properties of aryl bromides have a minor influence on the coupling reactions, the nature of arylboronic

Table 3—Suzuki-Miyaura cross-coupling reactions of various aryl halides with arylboronic acids using $1L_8$ as catalyst. [React. cond.: aryl halide (2.0 mmol); arylboronic acid (2.20 mmol); K_2CO_3 (6.0 mmol); water: 6 mL]

Entry	Ar-X	R	Yield[a] (%)
1	4-Bromonitrobenzene	H	86
2	4-Bromoacetophenone	H	92
3	4-Bromobenzaldehyde	H	84
4	4-Bromonitrobenzene	4-Cl	78
5	4-Bromonitrobenzene	4-Me	82
6	4-Bromonitrobenzene	$3-NO_2$	trace
7	Bromobenzene	H	94
8	4-Bromotoluene	H	84
9	4-Bromoanisole	H	86
10	2- Bromotoluene	H	61
11	2-Bromoanisole	H	53
12	3-Bromopyridine	H	75
13	3-Bromoquinoline	H	84
14	Iodobenzene	H	98
15	4-Iodonitrobenzene	H	98
16	4-Chloronitrobenzene	H	12
17	Chlorobenzene	H	14

[a]Isolated yield (avg. of two runs).

acids has a substantial influence on the overall performance of the catalyst. For example, when 4-bromonitrobenzene was used, phenylboronic acid was found to be the most efficient boronic acid producing 86 % of the coupling products (entry 1). On the other hand 4-chlorophenylboronic and 4-tolylboronic acid produced 78 and 82 % yield respectively (entries 4 & 5) and 3-nitrophenylboronic acid gave only negligible product formation (entry 6). It is interesting to note that, the complex **1L$_8$** also gave good result with heterocyclic substrates such as 3-bromoquinoline and 3-bromopyridine (entries 12 & 13). Similar to aryl bromides, the aryl iodides as substrate also produced excellent yield (entries 14 & 15). Although coupling reactions with aryl bromides and aryl iodides proceeded smoothly in water at room temperature to give the desired coupling product in good-to-excellent yields, under the same experimental condition the reactions between aryl chlorides with phenylboronic acid produced only very low yields (entries 16 & 17) of the cross-coupling products. It may be noted that traditionally aryl chlorides are less reactive than aryl bromides and aryl iodides in Suzuki-Miyaura reactions because of stronger carbon-chlorine bond over carbon-bromine and carbon-iodine[54].

Conclusions

In summary, we have explored the catalytic potential of eight primary amine-based palladium complexes for Suzuki-Miyaura cross-coupling reaction in aqueous medium at room temperature. In general, aromatic amines gave better results compared to aliphatic amines and the best catalytic result was obtained with triphenylmethylamine as ligand. Moreover, we found that there is an impressive relationship between the density-based reactivity descriptors (chemical hardness, chemical potential and electrophilicity index) of the ligands with the observed catalytic yield. Thus, we believe that our study will provide an important note for choosing suitable ligands for designing future catalysts for Suzuki-Miyaura reactions.

Supplementary Data

Supplementary data associated with this article, i.e., HOMO and LUMO diagrams of the ligands **L$_2$-L$_7$** (Fig. S1), are available in the electronic form at http://www.niscair.res.in/jinfo/ijca/IJCA_51A(11)1545 -1552_SupplData.pdf.

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