CHAPTER VI

A Pd(II) complex of *β*-cyclodextrin-based polydentate ligand: an efficient catalyst for Suzuki reaction in aqueous media*

6.1. Introduction

After the pioneering work of Reek and Breit on molecular self-assembly,[1, 2] the concept of supramolecular interaction has drawn much attention due to their high promising applicability in designing new ligands and their complexes. They prepared a library of self-assembled bidentate ligands by the way of supramolecular assembly and studied their catalytic performances in numerous catalytic reactions.[3, 4] It is well known that sugars have high water solubility and ability to recognize cell membrane for membrane transports; also such molecules when present in many antibiotics can interact with DNA. For all these reasons sugars and carbohydrates have gained much importance in clinical uses.[5] Likewise β-cyclodextrin or its derivatives and their complexes have found vast applications,[6,7] because of their aqueous solubility, bio-compatible nature with hydrophilic outer surface and lipophilic cavity as well as truncated cone or torus shape. By exploiting the reaction capabilities of -OH groups of β-cyclodextrin and formation of inclusion complexes many bidentate ligands can also be designed, *e.g.*, Patrigeon *et al*.[8] has developed supramolecular bidentate ligands and catalytically active Pt-complex in aqueous media. This is because hydrophobic species may easily be encapsulated inside the hydrophobic β-cyclodextrin cavity through the formation of supramolecular inclusion complexes subject to the size, substituents and orientation as well as mode of interactions of the hydrophobic species with the cavity.

It is well known that palladium is a versatile metal for homogeneous and heterogeneous catalyses.[9,10] Recently, Dindulkar *et al*. has developed a Pd-complex with supramolecular ligand and studied its catalytic activity in Mizoroki–Heck cross-coupling reactions in aqueous medium.[11] Pd(II) complexes were found to cleave proteins selectively[12] and some Pd(II) complexes were reported to have anti-bacterial,[13] anti-proliferative,[14] anti-trypanosomal,[15] anti-cancer and anti-tumor activities.[16,17] PdL_4 or PdL_2Cl_2 type coordination compounds were used in many catalytic processes, particularly for asymmetric catalysis[18] and C-C cross coupling reactions.[19] However, palladium catalysed reactions have some major drawbacks such as the use of toxic solvents, long reaction time and high temperature, *etc*.[20-22] From

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green chemistry parspective, water stands a naturally occurring low cost, non-toxic, non-flammable green solvent and potential replacement of most organic solvents.[19] Using water as a solvent with hydrophilic metal containing catalyst results in easy separation and recycling of the catalyst. Generally most of the Pd(II) complexes have low aqueous solubility that limits their catalytic efficiency in aqueous phase. Recently, Ibrahim *et al.* synthesized Pd(II) complexes which showed catalytic activities in the alkoxycarbonylation of various alkynes in aqueous medium.[23] Anitha *et al.* synthesized Pd(II) 9,10-phenanthrenequinone N-substitutedthiosemicarbazone/semicarbazone complexes and their catalytic efficiency was examined against N-arylation of imidazole.[24] Yang synthesized four heteroleptic Pd(II) complexes containing both N-heterocyclic carbenes and 1*H*-benzotriazole and their catalytic performance was investigated for Mizoroki–Heck and Sonogashira reactions. The results shows high catalytic activities for coupling of aryl bromides with alkenes and alkynes.[25] So, keeping their aspects of Pd(II) complexes in mind, herein this work we have reported the synthesis and physico-chemical characterization of a air stable water soluble Pd(II)-complex of a supramolecular *N*, *N*′, *O*-tridentate ligand (synthesized by spontaneous assembly of choline bromide and 2,6-diaminopyridine by exploitation of the hydrophobic character of β-cyclodextrin cavity) and its catalytic efficacy in Suzuki reaction in aqueous media. The complex works well in the cross-coupling reactions of different aryl halides and arylboronic acids; it was easily recovered and reused several times. As compared to some palladium catalyzed recations in aqueous media[26,27] the complex works effectivelly for water insoluble arylhalides for Suzuki reaction, bereft of any phase transfer catalyst and organic solvents.

6.2. Experimental section

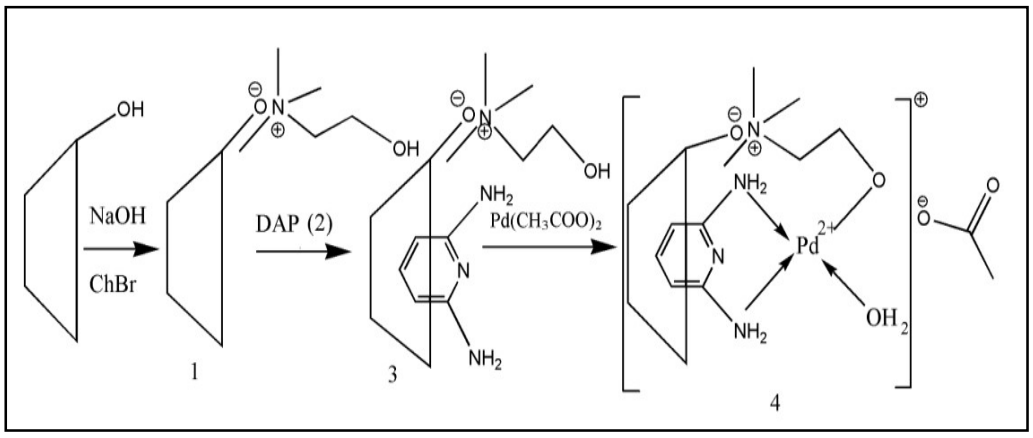
6.2.1. Materials and methods

All the chemicals were purchased from Sigma-Aldrich, Germany and BDH Chemicals Ltd., England and were used as received. Doubly distilled deionized water was used in all the experiments. Elemental micro-analyses (C, H and N) were conducted with a Euro VECTOR EA 3000 analyzer. Pd-content was determined by AAS (Varian, SpectraAA 50B) using standard Pd-solution from Sigma-Aldrich, Germany. FTIR spectra were recorded in KBr pellets with a Perkin-Elmer Spectrum FTIR spectrometer (RX-1) working in the range 4000-400 cm^{-1} at ambient temperature. UV-Visible spectra were recorded in a quartz cell (1 cm) on a Jasco (V-

530) double beam spectrophotometer equipped with a thermostated bath (maintained at 25±0.1 °C) using water as the reference solvent. During the spectrophotometric titration, the stepwise addition of metal ion solution (1×10^{-3} mol · L^{-1}) to 2 mL of a ligand solution (1×10^{-5} mol · L^{-1}) were done using a 2.5 μL pre-calibrated micropipette. The absorbance (*A*) of the solution was measured after each addition of the metal ion solution to the ligand solution. ^{1}H NMR spectra were recorded at ambient temperature on a Bruker Advance-II 400 MHz spectrometer by using D_2O as solvents and chemical shifts (δ) were quoted in ppm with respect to TMS. The surface morphology was studied using a Field Emission Scanning Electron Microscopy (FESEM, INSPECT F50, FEI, Netherlands). The purity of the ligand and Pd(II) complex were monitored by using TLC. The detailed descriptions of the various analytical and spectroscopic methods and instruments have been discussed in chapter II.

6.2.2. Synthesis

The synthesis path of β-cyclodextrin-based polydentate ligand and its Pd(II) complex are shown in Scheme 6.1.



Scheme 6.1. Syntheses of compounds 1, 3 and 4.

6.2.2.1. Synthesis of the ionic liquid [ChCD, 1]

An aqueous solution of NaOH (0.2116 g, 5.29 mmol) was added dropwise in a round bottom flask containing an aqueous suspension of β-cyclodextrin (6.0 g, 5.29 mmol) in doubly distilled deionized water (50 mL) with continuous stirring for 6-10 min. The suspension became gradually homogeneous and it turned slightly yellowish in colour when the addition was completed. Then a freshly prepared aqueous solution of Choline bromide (0.6 g) was added to it and heated with constant stirring at 80 °C

for 8h. After the reaction has ceased, the solvent was removed by distillation. The obtained wine coloured oily product was washed successively with isopropanol and diethylether to remove NaBr. After drying it overnight an orange coloured solid was obtained and was recrystalised to get the pure product from the aqueous solution. Yield: 50%

Anal. Calcd. for $C_{47}H_{83}NO_{36}$: C, 45.59; H, 6.70; N, 1.13; O, 46.56. Found: C, 45.25; H, 6.59; N, 1.05; O, 46.02. ^{1}H NMR (400MHz, D_2O): δ 4.983 (s, 7 H, H(1)), 4.742 (m, 7 H, OH(6)), 3.880 (m, 7H, H(3)), 3.857-3.796 (m, 21 H, H(6) and H(5)), 3.569 (m, 7H, H(2)), 3.515 (m, 7H, H(4)), 3.548 (s, 1H, -O<u>H</u> of choline), 3.495 (t, 2H, -C<u>H</u>$_2$OH of choline), 3.118 (t, 2H, $(CH_3)_3N^+$-C<u>H</u>$_2$- of choline), 1.829 (s, 9H, -N^+(C<u>H</u>$_3$)$_3$ of choline). IR (ν/cm^{-1}): 3393(b), 2930(s), 1647(m), 1397(b) , 1214(w), 1159(s), 746(s).

6.2.2.2. Synthesis of the Supramolecular Complex 1⊂2 (3)

A 50 mL round bottom flask containing a mixture of ionic liquid (1) (1 g, 0.782 mmol) and 2,6-diaminopyridine (2) (85.3 mg, 0.7826 mmol) in water was heated at 50 °C for ~ 6 hour. From the reaction mixture, a reddish brown precipitate was separated by filtration. The precipitate was washed with ethanol several times to remove excess of the amine. Then it was dried and kept in a vacuum desiccator at room temperature. Yield: 66%

Anal. Calcd for $C_{52}H_{90}N_4O_{36}$: C, 46.30; H, 6.68; N, 4.16; O, 42.79. Found: C, 45.93; H, 6.53; N, 3.92; O, 42.24. ^{1}H NMR (400MHz, D_2O): δ 4.997 (s, 7H, H(1)), 4.780 (m, 7H, OH(6)), 3.781(m, 7H, H(3)), 3.857 (m, 7H, H(5)), 3.801 (m, 14 H, H(6)), 3.54 (m, 7H, H(2)), 3.503 (m, 7H, H(4)), 3.532 (s, 1H, -O<u>H</u> of choline), 3.486 (t, 2H, -C<u>H</u>$_2$OH of choline), 3.123 (t, 2H, $(CH_3)_3N^+$-C<u>H</u>$_2$- of choline), 1.840 (s, 9H, -N^+(C<u>H</u>$_3$)$_3$ of choline), 7.305-7.285 (d, 1H, H_a), 5.995-5.975 (dd, 2H, H_b). IR (ν/cm^{-1}): 3368(b), 2930(s), 1624(s), 1416(m), 1370(s), 1333(w), 1205(w), 781(s), 750(s).

6.2.2.3. Synthesis of [κ^3-N, N$^/$, O-Pd(1⊂2)H_2O]OAc (4)

Palladium acetate (30.0 mg, 0.01317 mmol) was added to the 1 equivalent aqueous ethanolic solution of ligand 1⊂2 (3) (150 mg, 0.01317 mmol) and heated at 60 °C for ~ 3h in a round bottom flask. As the reaction proceeds, the color of the solution changed from reddish brown to chocolate brown. After the completion of reaction, acetone (50 mL) was added to the solution and chocolate colored product was separated by filtration. The product was recrystalised several times from aqueous

solution and ultimately chocolate colored small crystalline solid was obtained. Yield: 69%.

Anal. Calcd for $C_{54}H_{95}N_4O_{40}Pd$: C, 41.94; H, 6.15; N, 3.62; O, 41.42; Pd, 6.90. Found: C, 40.35; H, 5.79; N, 3.49; O, 40.85; Pd, 6.24. ^{1}H NMR (400MHz, D_2O): δ 4.910-4.902 (m, 7H, H(1)), 4.761 (m, 7H, OH(6)), 3.784 (m, 7H, H(3)), 3.715 (m, 7H, H(5)), 3.762 (m, 14 H, H(6)), 3.497 (m, 7H, H(2)), 3.477 (m, 7H, H(4)), 2.558 (t, 2H, -C$\underline{H_2}$O- of choline), 2.061 (t, 2H, $(CH_3)_3N^+$-C$\underline{H_2}$- of choline), 1.011-0.996 (d, 9H, -N^+(C$\underline{H_3}$)$_3$ of choline), 4.552 (broadsinglet, 2H, -NH_2),[7.305-7.285(d,1H,H_a,), 5.995-5.975(dd ,2H,H_b)] lower intensity. IR (ν/cm^{-1}): 3314(bs), 2917(s), 1170(w). 1002(w), 939(s), 527.5(s), 419.5(s).

6.2.3. Catalytic Activity

The detailed procedure for Suzuki reaction in water using aryl halide (1.0 mmol), aryl boronic acid (1.2 mmol), the complex (4) (3 mol%), K_2CO_3 (2.0 mmol) and water (3 mL) has been given in Chapter II (2.2.8.1). The separation and purification of products and the recovery procedure of the catalyst were also described in chapter II (section 2.9). The products were analyzed with ^{1}H NMR spectra (shown in Figures 6.10 - 6.16).

6.2.3.1. Recovery of catalyst

After the extraction of the products, the catalyst was reprecipitated by the addition of 10 mL of acetone to the aqueous layer containing the catalyst. The recovered catalyst was filtered, washed with acetone and dried in a vacuum and reused for Suzuki reaction.

6.3. Results and discussion

Scheme 6.1 depicts the synthesis of a new β-cyclodextrin based polydentate ligand and its Pd(II) complex through supramolecular assemblies. The first step of the synthetic route involves the synthesis of the ionic liquid ChCD (1) by the reaction of β-cyclodextrin with Choline bromide in basic medium. On addition of 1equiv of NaOH, the –OH group at 2-position of β-cyclodextrin readily deprotonates.[28] and reacts with equimolar amount of choline ion to afford the ionic liquid ChCD (1) and NaBr.[29] Next 2,6-diaminopyridine (2) was reacted with ChCD (1) to form the inclusion complex 1⊂2 (3), which can act as a *N*, *N′*, *O*- tridentate ligand. The supramolecular ligand 1⊂2 (3) was then reacted with $Pd(OAc)_2$ in water-ethanol mixture to give a Pd^{2+}complex [κ^3-*N*, *N′*, *O*-Pd(1⊂2)H_2O]OAc (4). These compounds

(1, 3 and 4) were characterized by various physico-chemical and spectroscopic methods like elemental analysis, FESEM, UV-Visible, FTIR, ^{1}H NMR spectroscopy.

6.3.1. FTIR spectra

FTIR spectra of β-cyclodextrin and the compounds (1, 3 and 4) were recorded in KBr pellet in the region 4000 to 400 cm^{-1} at ambient temperature. FTIR spectra of β-cyclodextrin, ChCD (1) and the compound 1⊂2 (3) are shown in Figure 6.1. In the FTIR spectrum of ChCD (1) peaks appearing in the region of 1200-1050 and 769-695 cm^{-1} were assigned to the C-O stretching vibrations and out plane bending vibration of O-H of primary alcohol group in choline moiety, respectively. The broad peak at around 1420-1330 cm^{-1} was assigned to the coupling of the band due to in-plane bending vibration of –OH with the band for C-H wagging vibrations. The C-N stretching band of quaternary amine of Choline moiety appeared at 1214 cm^{-1}.[30] The broad absorption band appearing at 3400-3200 cm^{-1} can be assigned to -OH stretching vibrations of β-cyclodextrin and suggests the presence of strong intermolecular hydrogen bond interactions between these -OH groups of *β*-CD.[31,32] However, this band appeared to be more broader for compound (1) as compared to that for β-cyclodextrin (Fig 6.1); this fact can tentatively be ascribed to the interaction between the quarternary N-atom of the Choline moiety and the deprotonated –OH or O^{-}-group at the position 2 of *β*-CD.[33] The peaks appearing at around 1342-1200 and 781 cm^{-1} for compound (3) can be assigned to the C-N stretching and the N-H waging vibrations of aromatic amine moiety present in the structure of the compound (3). This fact simply corroborates with the inclusion of 2, 6-diaminopyridine (2) in the β-cyclodextrin cavity of ChCD (1) with concomitant breaking of hydrogen bonds inside the cavity of β-cyclodextrin moiety and thus the broad peak appearing in the region of 3400-3200 cm^{-1} becomes less broader than that for ChCD (1). Also the peak appearing at 750, 1205, 1370 and 1416 cm^{-1} can tentatively be assigned for choline moiety present in the compound 1⊂2 (3). FTIR spectrum of the Pd(II) complex (4) is illustrated in Figure 6.2. Two new peaks appearing at 527.5 and 419.5 cm^{-1} can presumably be assigned to Pd-N and Pd-O stretching vibrations, respectively.[34] The stretching vibration of C-O bond of choline moiety got shifted from 1205 to 1180 cm^{-1} suggesting the formation of Pd-O bond. These stretching vibrations proved of the involvement of the deprotoneted O-atom of choline moiety and the N-atoms of 2,6-diaminopyridine moiety in the coordination with the Pd^{2+} ion in the complex (4). Two peaks appearing at 939 cm^{-1} and 1002 cm^{-1} are most probably due to the stretching

and rocking vibrations of water molecule that coordinates with Pd(II) ion in the complex (4).[34]

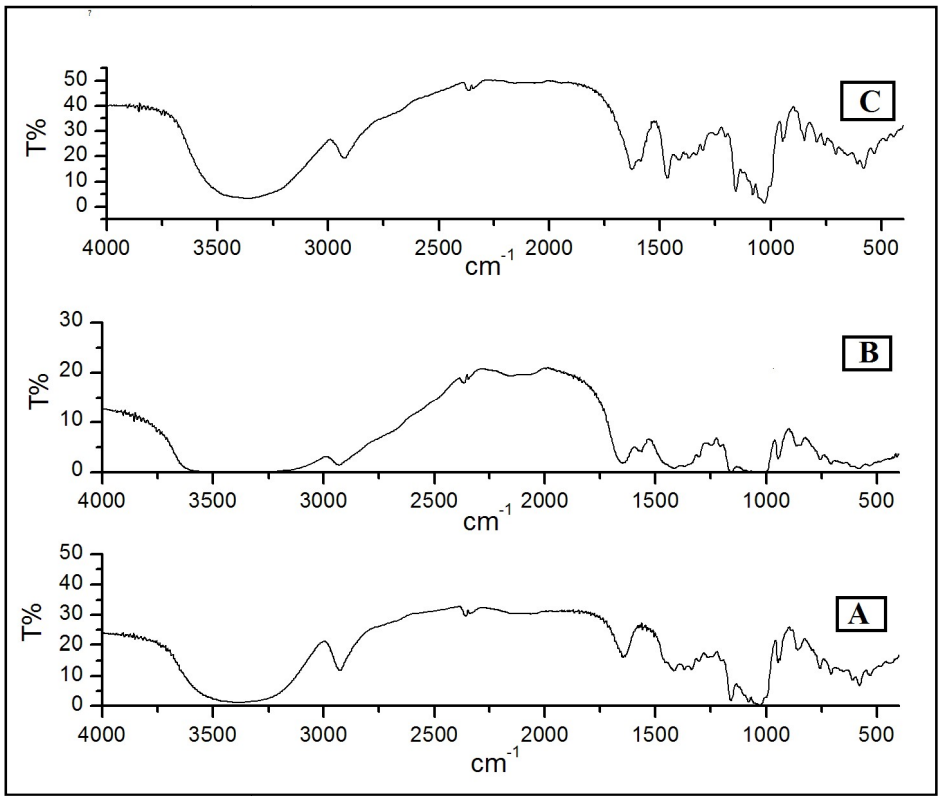


Fig 6.1. FTIR spectra of: A, *β*-cyclodextrin (*β*-CD); B, ChCD (1); C, 1⊂2 (3).

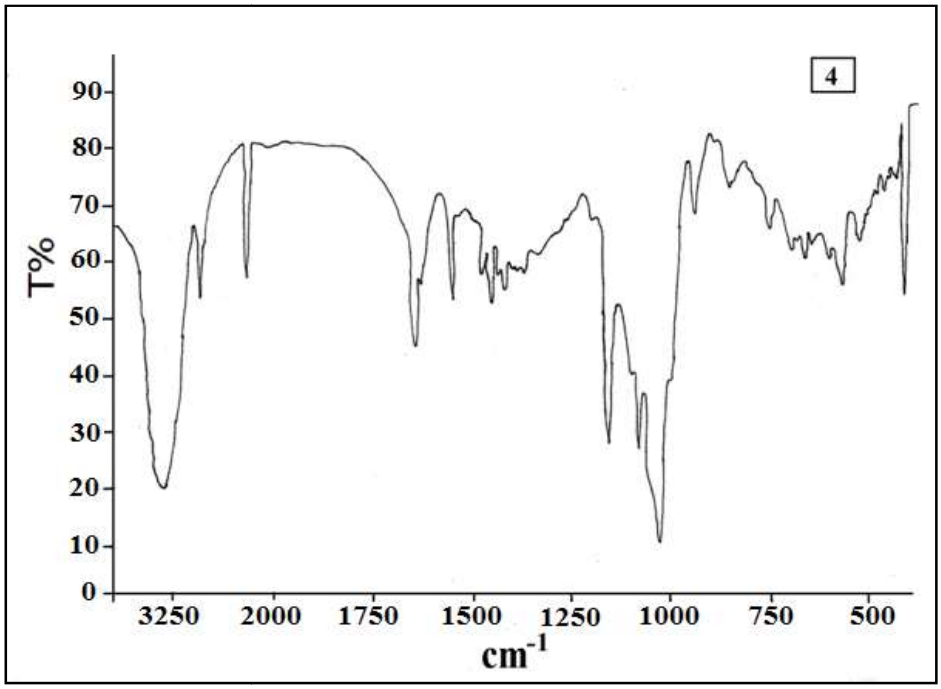


Fig 6.2. FTIR spectrum of [κ^3-*N*, *N*′, *O*-Pd(1⊂2)H_2O]OAc (4).

6.3.2. NMR spectra

^{1}H NMR spectra of the ionic liquid ChCD (1), the ligand 1⊂2 (3) and the complex (4) are given in Figures 6.3 - 6.5 and the chemical shifts observed for (H1-H6) are listed in Table 6.1.

Table 6.1. ^{1}H Chemical shifts (in ppm) of: β-cyclodextrin (*β*-CD), ChCD (1), 2,6-diaminopyridine , 1⊂2 (3), [κ^3-*N*, *N*′, *O*-Pd(1⊂2)H_2O]OAc (4).

H	β-CD [39]	ChCD(1)	1⊂2 (3)	Pd(II) complex (4)
1	5.154	4.983	4.997	4.910, 4.902
2	3.700	3.569	3.540	3.497
3	3.920	3.880	3.781	3.784
4	3.600	3.515	3.503	3.477
5	3.825	3.796	3.789	3.715
6	3.900	3.857	3.801	3.762
OH				
2	5.750			
3	5.650			
6	4.500	4.742	4.780	4.761

The peak for -OH proton at position 2 of β-cyclodextrin disappeared for the compound (1) but the peak for -OH proton at position 6 of β-cyclodextrin shifted slightly to downfield (δ = 4.742); this suggests that the deprotonation occurs at position 2 of β-cyclodextrin. While the peak for H2 shifted to downfield by $\Delta\delta$ = 0.131, the peak for H3 shifted slightly to downfield by $\Delta\delta$ = 0.04 ppm. These shifts in δ-values suggest that quaternary N-atom of Choline moiety remain close to the deprotonated –OH or O^--group at C2 of *β*-CD. ^{1}H-peaks for $(CH_3)_3N^+$-C<u>H</u>$_2$ and C<u>H</u>$_3$-groups attached to N-atom of choline moiety (that generally appear at 3.53 and 3.20 ppm[35]) were shifted to 3.118 and 1.829 ppm, respectively for the compound (1), probably due to electrostatic interactions between quaternary N-atom of choline moiety and O^--group of β-cyclodextrin.[36] The peak at 3.515 and 3.495 ppm arises for -O<u>H</u> and -C<u>H</u>$_2$OH group of choline moiety respectively. It is well known that H3 and H5 are located inside the hydrophobic cavity of β-cyclodextrin and H1, H2 and H6

remain outside of the β-cyclodextrin cavity. So the H5 and H3 are mostly affected due to inclusion. ^{1}H NMR of the compound (3) showed that the peak for H3 shifted by an amount $\Delta\delta$ = 0.099 ppm and that for H5 shifted by an amount $\Delta\delta$ = 0.007 ppm (Table 6.1); those shifts suggest that inclusion of pyridine ring of the amine affects H3 more than H5, *i.e.*, inclusion of 2,6-diaminopyridine (2) occurs through the secondary rim of β-cyclodextrin cavity in ChCD (1)[30,37,38] and suggests partial inclusion of pyridine ring in the β-cyclodextrin cavity.[39] The appearance of two doublets at $\delta \approx$ 7.305-7.285 and 5.995-5.997 ppm, respectively are most probably due to H_a and H_b protons of 2,6-diaminopyridine moiety (Figure 6.4). The peak for $-NH_2$ group of 2,6-diaminopyridine that appears at around $\delta \approx$ 5.32 ppm has eventually merged with the peaks of β-cyclodextrin moiety.[40] In ^{1}H NMR spectrum of the complex (4), it is obvious that the intensity of the doublet peaks of amine at $\delta \approx$ 7.305-7.285 ppm and 5.995-5.997 ppm decrease but the appearance of a broad singlet peak at 4.552 ppm suggests coordination of Pd^{2+} ion with the N-atoms of two NH_2 groups of 2,6-diaminopyridine moiety. The peak at 3.486 and 3.123 ppm for -C<u>H$_2$</u>OH and $(CH_3)_3N^+$-C<u>H$_2$</u> of choline moiety shifted downfield with δ values 2.558 and 2.061 ppm. Also the peak for CH_3-groups attached to the N-atom of choline moiety shifted downfield and splited into a doublet with δ values 1.011 and 0.996 ppm; these shifts and splittings indicate that –OH or O^--group of choline moiety coordinates with Pd^{2+} ion in the complex (4).

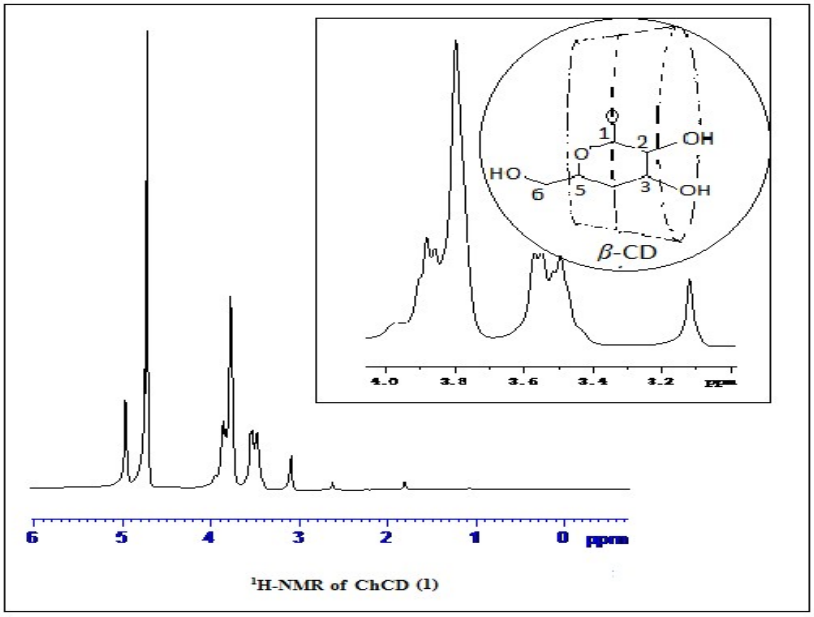


Fig 6.3. ^{1}H NMR (400MHz, D_2O) of ChCD (1).

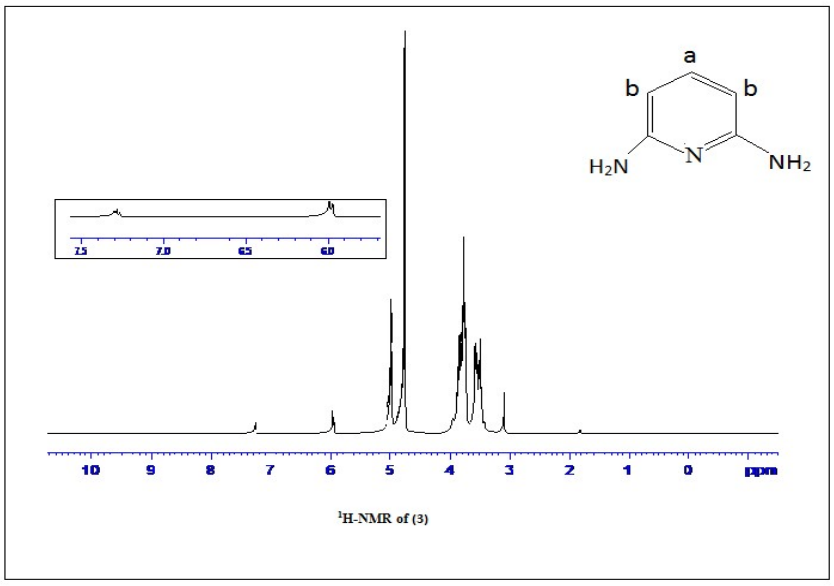


Fig 6.4. ^{1}H NMR (400MHz, D_2O) of 1⊂2 (3).

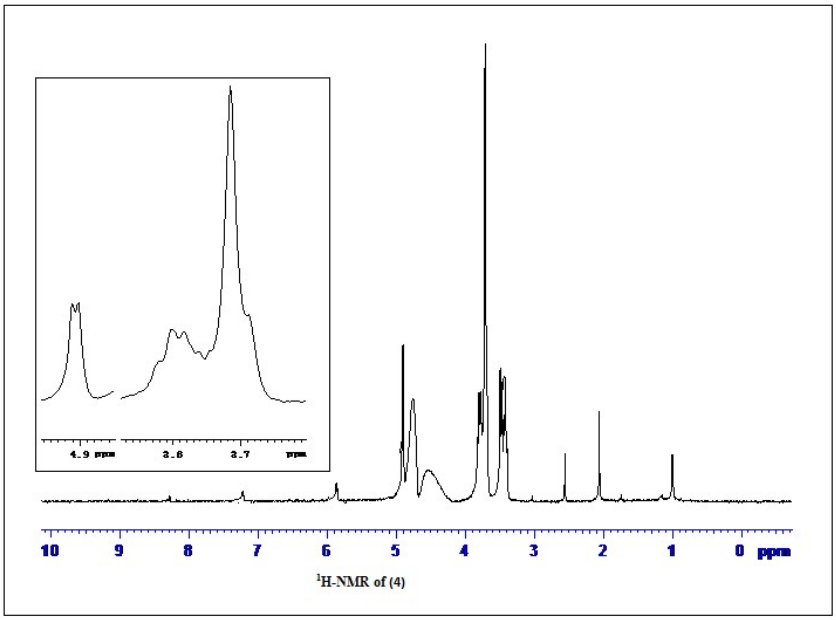


Fig 6.5. ^{1}H NMR (400MHz, D_2O) of [κ^3-*N*, *N*′, *O*-Pd(1⊂2)H_2O]OAc (4).

6.3.3. UV-visible spectra

UV-visible spectra of β-CD, 2,6-diaminopyridine, ChCD (1), ligand 1⊂2 (3) and its Pd(II) complex (4) in water were illustrated in Figure 6.6. It is evident that ChCD (1) shows almost no absorption in UV-Visible range like β-cyclodextrin.[32,41] However, the absorption intensity for the inclusion complex (3) is more than that for 2,6-diaminopyridine. The UV-Visible spectra of ligand (3) showed two characteristic

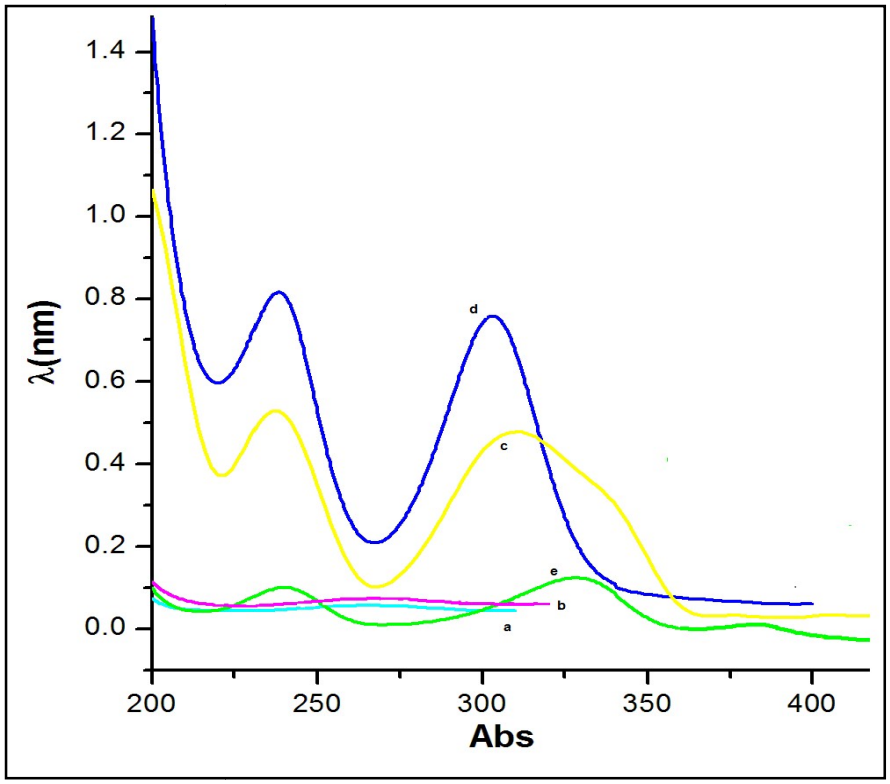


Fig 6.6. Absorption spectra of: (a), β-cyclodextrin (β-CD); (b), ChCD (1); (c), 2,6-diaminopyridine; (d), 1⊂2 (3) and (e), [κ^3-*N*, *N*′, *O*-Pd(1⊂2)H_2O]OAc (4).

bands at around 238 nm (π→π*) and 303 nm (n→π*) like those obtained for 2,6-diaminopyridine system.[42] The absorption spectrum of Pd(II) complex (4) shows three peaks at 240, 328.5 and 398 nm. While the absorption peak at 240 nm can be assigned to intraligand π→π* transitions, the peak at 398 nm is probably due to a combination ligand to metal charge transfer stand in support of a square planar geometry for the metal ion (d^8 system).[34,43,44] Again bathochromic shift for the peak from 303 to 328.5 nm suggests the coordination of Pd^{2+} ion with the N-atom of $–NH_2$ groups in the ligand (3). Interestingly the peaks at 238 nm of the ligand (3) remain almost same in the complex (4) suggesting no interaction between the N-atom of the pyridine ring of the ligand (3) with the Pd^{2+} ion.[42,45]

6.3.4. Apparent formation constant and stoichiometry

The apparent formation constant for the inclusion complex (3) was determined by UV-visible spectrophotometric titration of a solution of 2,6-diaminopyridine (9×10^{-3} mol · L^{-1}) with several solutions [(0-6)× 10^{-5} mol · L^{-1}] of ChCD (1). The absorbance of the solutions were measured at 238 nm against a reagent blank, *i.e.*, solutions with identical reagent concentration but without 2,6-diaminopyridine.

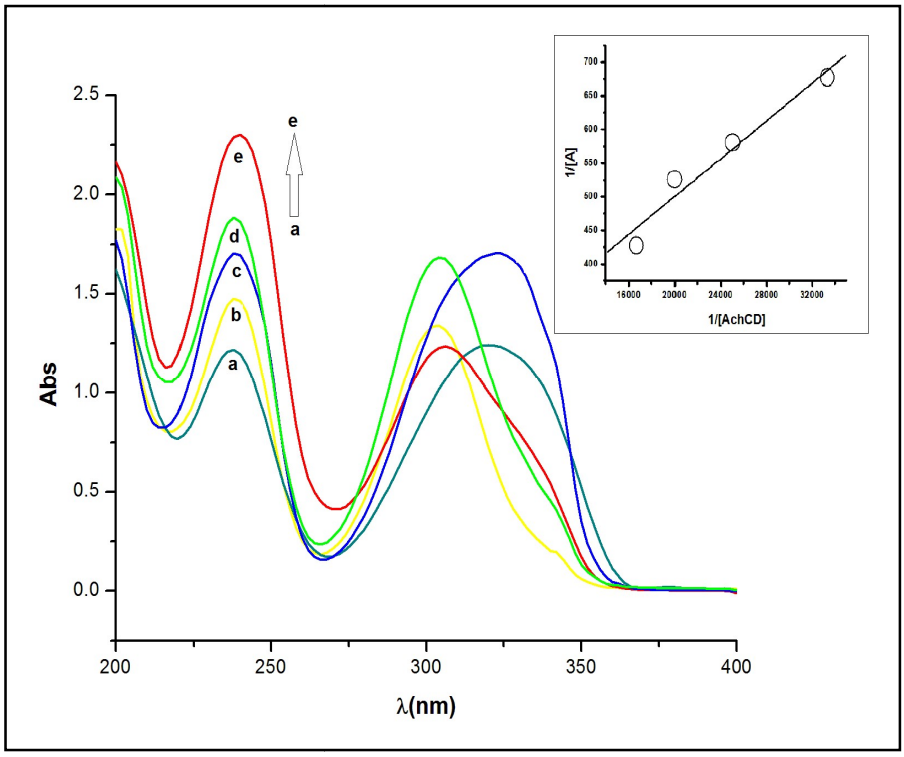


Fig 6.7. Absorption spectra of 2,6-diaminopyridine with various concentration of ChCD: (a), 0 M; (b), 3×10^{-5} M; (c), 4×10^{-5} M; (d), 5×10^{-5} M and (e), 6×10^{-5} M. Inset: Plot for $1/A$ against 1/[ChCD] for the formation of 1⊂2 (3).

The absorption spectra of inclusion complex (3) at different concentrations of ChCD (1) have been depicted in Figure 6.7. It shows that the intensity gradually increases as the concentration of ChCD (1) in the solution increases upon the formation of the inclusion complex (3). The stoichiometry and apparent formation constant of the complex (3) were determined from Hildebrand-Benesi equation:[32, 41]

$$\frac{1}{A} = \frac{1}{\varepsilon K\,[G^0][\mathrm{ChCD}]} + \frac{1}{\varepsilon [G^0]}$$

where A is the absorbance for the amine at each ChCD (1) concentration; $[G^0]$, K, [ChCD] and ε are the initial concentration of amine, apparent formation constant, the concentration of ChCD (1) and the molar absorptivity, respectively. Thus a linear regression ($R^2 = 0.953$)[29,39,28] of $1/A$ *versus* 1/ [ChCD] data gives the stoichiometric ratio (the amine:ChCD =1:1) and the apparent formation constant [$(1.554 \pm 0.036) \times 10^{-4}$ mol · L^{-1}] for the inclusion complex (3).

The stoichiometry of the complex (4) has been also determined by spectrophometric titration (mole-ratio method). The changes in the absorption spectrum of the ligand (3) (initially 1×10^{-5} mol · L^{-1}) against concentrations of

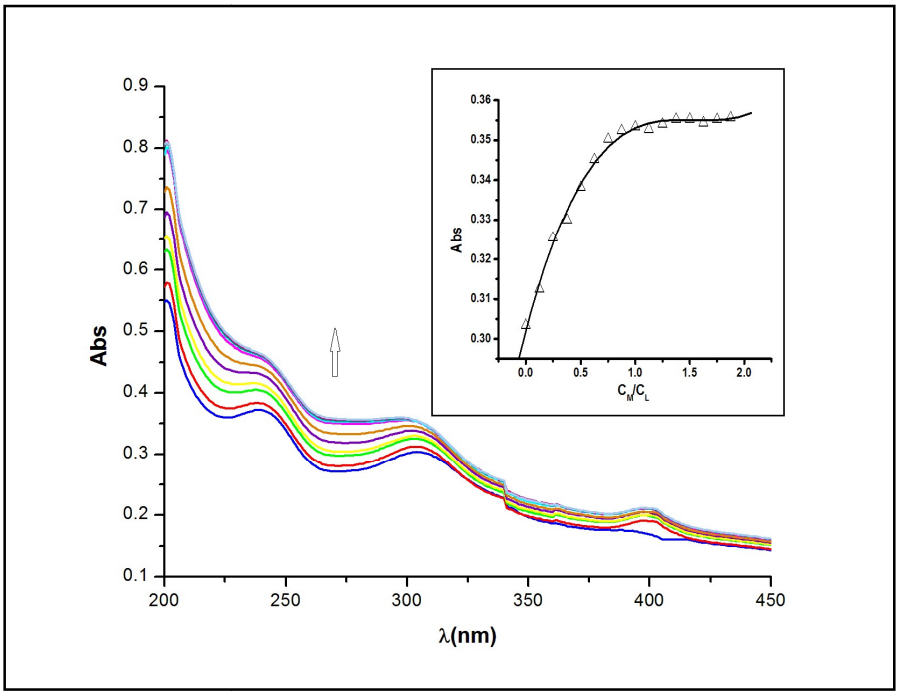


Fig 6.8. UV–Vis spectra of the ligand 1⊂2 (3) (1×10^{-5} mol · L^{-1}) in the presence of increasing concentrations of Pd(II) ions. Inset: Absorbance plot for the ligand 1⊂2 (3) with Pd(II) ion against *c*M:*c*L.

$Pd(OAc)_2$ (1×10^{-3} mol · L^{-1}) added by 2.5 μL repeatedly. During the spectrophometric titration, complex formation was indicated by a gradual increase in the intensity of 238 and 303 nm peaks as shown in Figure 6.8. The spectrophotometric data was analyzed with the absorbance values at λ = 238 nm as shown in Figure 6.8 (inset), which suggests the stoichiometry to be 1:1.[46] Also using the ($c_M c_L$/A *versus* c_M) data and following a literature method,[43] the stability constant of the complex (4) was found to be $\log K_f = 6.39 \pm 0.02$ at 25 °C.

6.3.5. Scanning electron microscopy

The FESEM images of ChCD (1), ligand 1⊂2 (3) and its Pd(II) complex (4) are shown in Figure 6.9. The surface morphology of ChCD (1) seems to be irregular suggesting it to be amorphous in nature but that of the inclusion complex or the ligand (3) is comparatively more regular and crystalline in nature than that of ChCD (1). Interestingly the surface of the complex (4) is clearly regular and seems to be crystalline in nature.

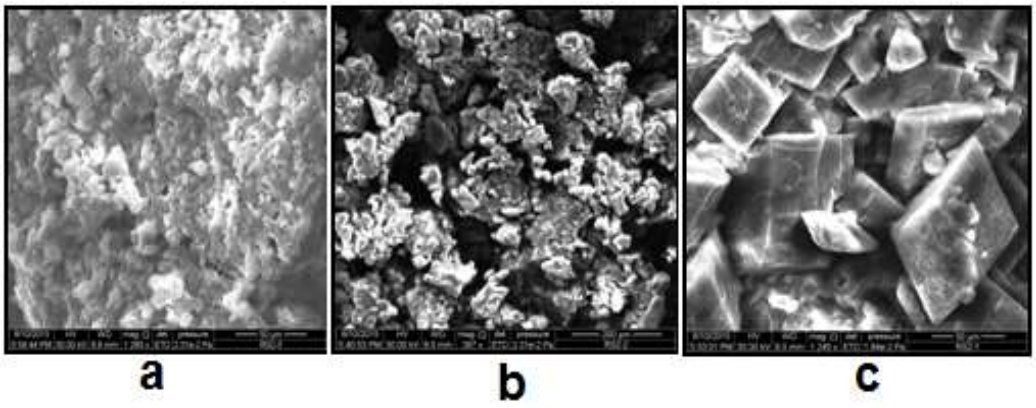
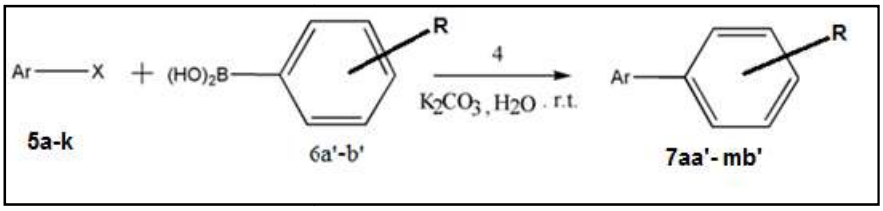


Fig 6.9. SEM images of: (a), ChCD (1); (b), 1⊂2 (3) and (c), [κ^3-*N*, *N'*, *O*-Pd(1⊂2)H_2O]OAc (4).

6.3.6. Suzuki reaction catalysis

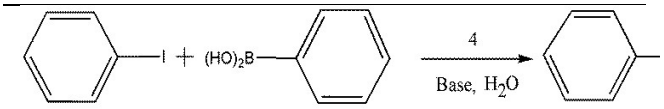
It is well known that Suzuki reaction depends on the type of base used and amount of the catalyst. So the reaction conditions were optimized by performing model reaction between iodobenzene (5a) and phenylboronic acid (6a'). Different experimental reaction conditions and results are summarized in Table 6.2. Using K_2CO_3 as base and 3 mol% of the complex (4) results in the optimum conversion at room temperature with good to excellent yield of biphenyl (7aa') (Table 6.2, entry 6). However, the product yields did not increase further by raising the catalyst concentration upto 5 mol%. Using 1 mol% of the catalyst also gave the good yield but it is not possible to recycle the catalyst after two cycles under these conditions. So, for Suzuki reaction the optimum loading for the catalyst was 3 mol%. The effictiveness the catalyst (4) in the Suzuki reaction in aqueous phase was investigated by using different arylhalide and arylboronic acids as substrates (Scheme 6.2) and the results are shown in Table 6.3.



5a Ar = C_6H_5, X = I
5b Ar = 4-$NO_2C_6H_4$, X = I
5c Ar = 4-$CH_3C_6H_4$, X = I
5d Ar = C_6H_5, X = Cl
5e Ar = 4-$NO_2C_6H_4$, X = Cl
5f Ar = 4-$CH_3C_6H_4$, X = Cl
5g Ar = C_6H_5, X = Br
5h Ar = 4-$NO_2C_6H_4$, X = Br
5i Ar = 4-$CH_3C_6H_4$, X = Br
5j Ar = 4-$OCH_3C_6H_4$, X = I
5k Ar = 2- $CH_3C_6H_4$, X = Br
5l Ar = 2,6-$(CH_3)_3C_6H_3$, X = Br
6a' R=H
6b' R= 3,4,5-$(OCH_3)_3$

Scheme 6.2. Suzuki reactions catalysed by the complex (4) in aqueous medium.

Table 6.2. Optimization of the reaction condition for Suzuki reaction catalyzed by complex (4)[a]



5a 6a' 7a

Entry	4 (mole%)	Base	Yield (%)[b]
1	0.1	Et_3N	68
2	0.1	NaOH	63
3	0.1	K_2CO_3	79
4	0.5	K_2CO_3	84
5	**1**	**K_2CO_3**	**84**
6	**3**	**K_2CO_3**	**85**
7	5	K_2CO_3	86

[a]Reaction conditions: 5a (1.00 mmol), 6a (1.2 mmol), **4** (x mole%), base (2.00 mmol),deionized water (3 mL), 35 min, room temparature. [b]Isolated yield.

Actually, it has been found that, for the chloro (5f) and bromo benzene (5g) the reaction takes longer time to complete and gave lesser yield than that for iodobenzene (5a) under same set of reaction conditions. Similar approach has also been applied for some substituted aryl halides containing electron-withdrawing or electon-donating groups, *e.g.*, 4-nitro, 4-methyl, 4-methoxy (Table 6.3, entries 4-9, 13). Reactions of different substituted iodobenzenes (5a-c, 5j-l) and arylboronic acids gave the good to excellent yields of corresponding coupled products (72-87%). The products are confirmed by ^{1}H NMR spectra (some of them are shown in Figure 6.10 - 6.16). This catalyst is also effective for cross-coupling reactions with sterically hindered aryl bromides (Table 6.3, entries 14, 15) but requires longer time and gives lower yields than other substrates studied. Using substituted boronic acid we also found good yields for the cross-coupling products (Table 6.3, entries 10, 11, 12). Therefore based on the above facts, this catalyst was observed to a work effectivelly for water insoluble arylhalides in Suzuki reacton as far as reaction time (lesser) and optimum load are concerned, when compared to other palladium catalyzed recations in aquous media.[39,40]

Table 6.3. Suzuki reaction between aryl halides (5) and arylboronic acids (6) catalyzed by complex (4) in water[a]

Sl. no.	X	Ar	R	Product	Time (min)	Yield[b](%)
1	Cl	C_6H_5	H	7aa’	55	71
2	Br	C_6H_5	H	7aa’	50	75
3	I	C_6H_5	H	7aa’	35	84
4	I	4 $CH_3C_6H_4$	H	7ca’	30	72
5	I	4-$NO_2C_6H_4$	H	7ba’	40	87
6	Br	4 $CH_3C_6H_4$	H	7ca’	50	69
7	Br	4-$NO_2C_6H_4$	H	7ba’	55	76
8	Cl	4 $CH_3C_6H_4$	H	7ca’	55	65
9	Cl	4-$NO_2C_6H_4$	H	7ba’	60	73
10	Cl	C_6H_5	3,4,5-$(OCH_3)_3$	7ab’	50	72
11	Br	C_6H_5	3,4,5-$(OCH_3)_3$	7ab’	40	74
12	I	C_6H_5	3,4,5-$(OCH_3)_3$	7ab’	35	77
13	I	4-$OCH_3C_6H_4$	H	7ja’	40	86
14	Br	2-$CH_3C_6H_4$	H	7ka’	70	66
15	Br	2,6-$(CH_3)_2C_6H_3$	H	7la’	150	58

[a]Reaction conditions: arylhalide (1.00 mmol), arylboronic acid (1.2 mmol), **4** (3 mole%), K_2CO_3 (2.00 mmol), deionized water (3 mL), room temperature. [b]Isolated yield.

Various coupling products were easily separated from the aqueous phase (containing the catalyst) by solvent extraction with hexane and ethyl acetate. Addition of acetone to the aqueous phase helps in the precipitation of the catalyst (4) from the aqueous phase. The catalyst was found to have sufficient catalytic activities (Table 6.4) even after 4 cycles although leaching of the catalyst during its extraction from the aqueous phase decreases its catalytic activities.

Table 6.4. Reusability of the complex (**4)** for the Suzuki reaction.

Run	1	2	3	4
%Yield[a] of 7aa’	90	87	84	81

[a]Isolated yield.

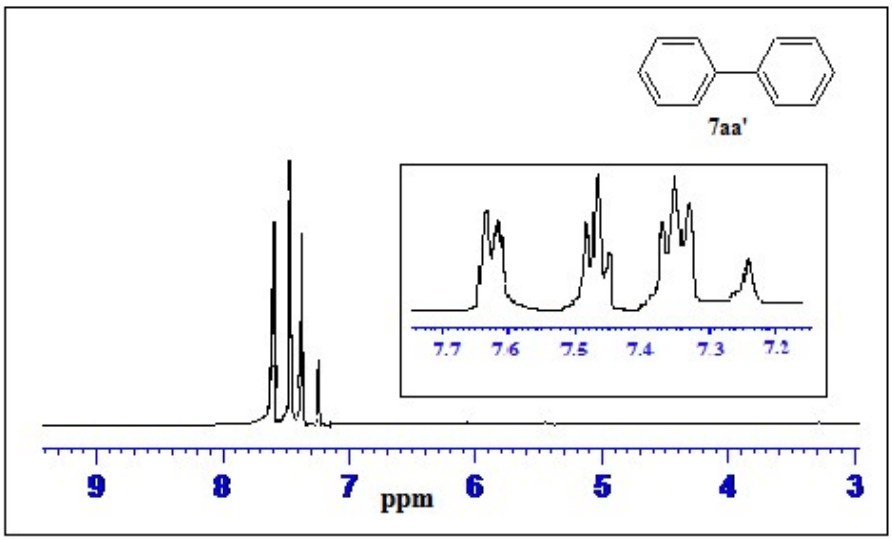


Figure 6.10: ^{1}H NMR (400MHz, $CDCl_3$) of biphenyl (7aa'): δ 7.65 – 7.60 (m, 2H), 7.48 – 7.44 (m, 2H), 7.37 – 7.32 (m, 1H).

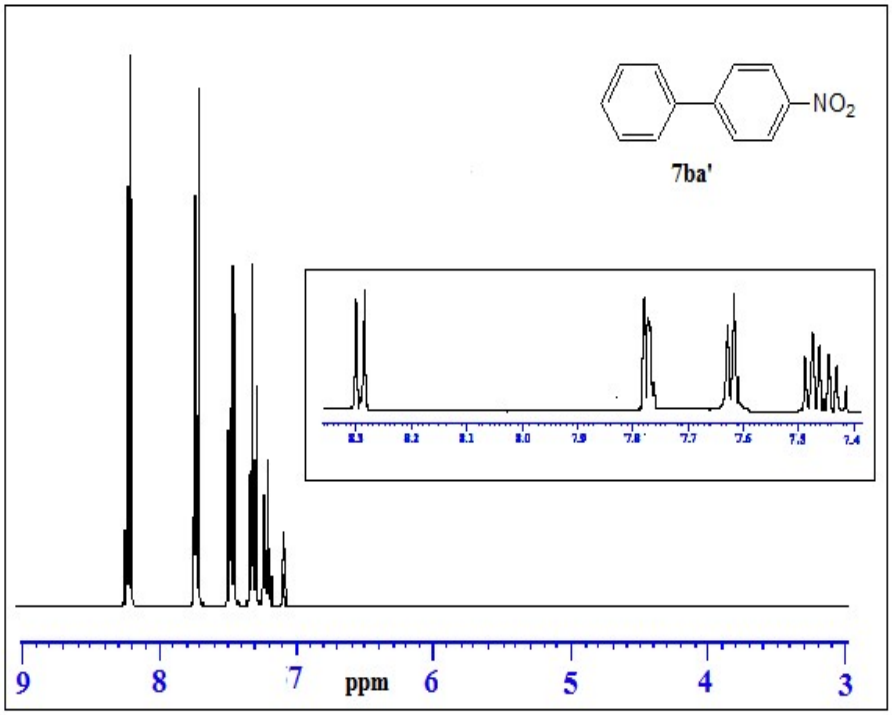


Figure 6.11. ^{1}H NMR (400MHz, $CDCl_3$) of 4-nitrobiphenyl (7ba'): δ 8.28-8.31 (dt, 2H), 7.77-7.78 (dt, 2H), 7.62 – 7.64 (m, 2H), 7.49 – 7.45 (m,3H).

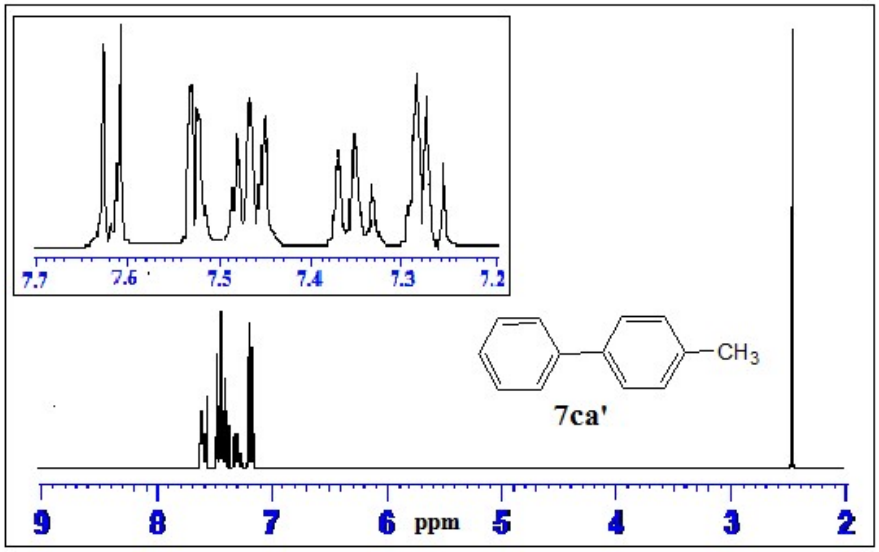


Figure 6.12. ^{1}H NMR (400MHz, $CDCl_3$) of 4-methylbiphenyl (7ca'): δ 7.63– 7.60 (m, 2H), 7.54 – 7.52 (m, 2H), 7.50 – 7.44 (m, 2H), 7.38 – 7.34 (m, 1H), 7.27-7.29 (d, 2H), 2.45 (s, 3H).

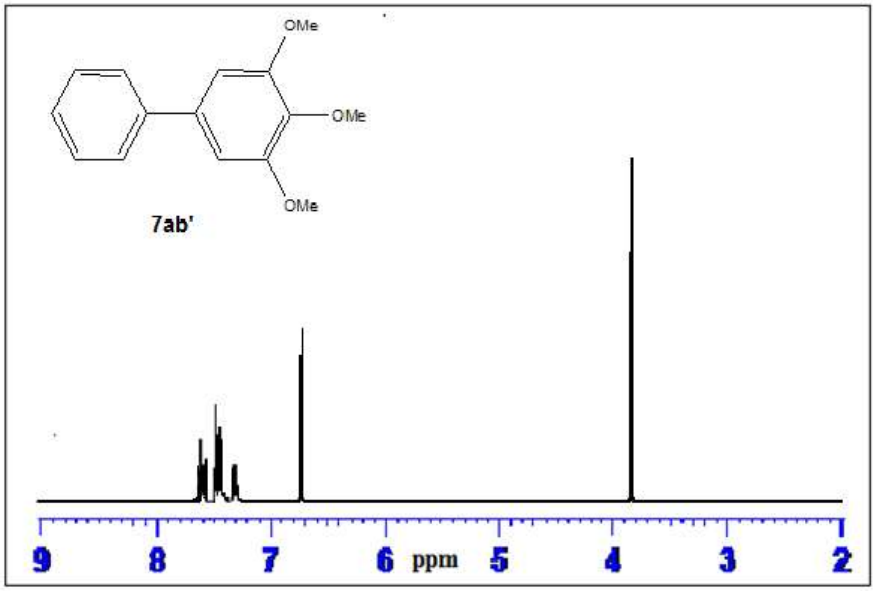


Figure 6.13. ^{1}H NMR (400MHz, $CDCl_3$) of 3,4,5-Trimethoxy-1,1'-biphenyl (7ab′): δ 7.65 – 7.55 (m, 2H), 7.51 – 7.45 (m, 2H), 7.27 – 7.32 (m, 1H), 6.72 (s, 2H), 3.87 (s, 6H), 3.82 (s, 3H).

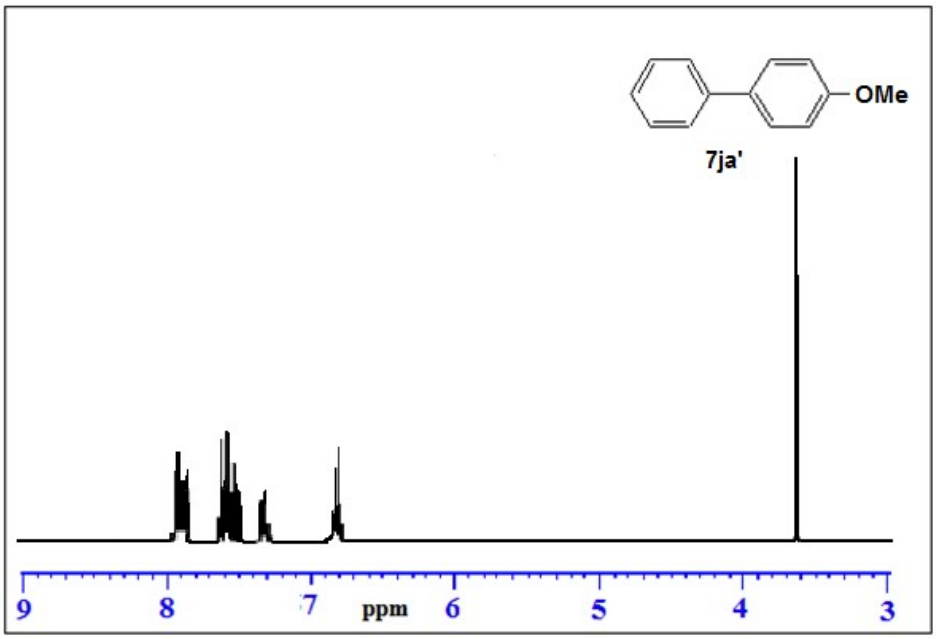


Figure 6.14. ^{1}H NMR (400MHz, $CDCl_3$) of 4-methoxybiphenyl (7ja'): δ 7.92 – 7.83 (m, 4H), 7.65 – 7.47 (m, 2H), 7.37 –7.29 (m, 1H), 6.84-6.79 (dt, 2H), 3.73 (s, 3H).

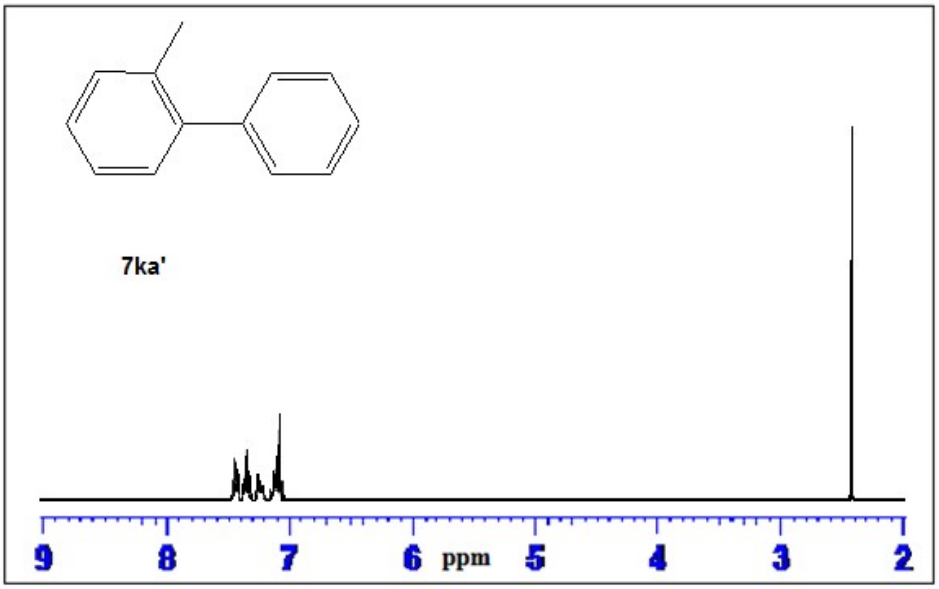


Figure 6.15. ^{1}H NMR (400MHz, $CDCl_3$) of 2-methylbiphenyl (7ka'): δ 7.49 – 7.41 (m, 2H), 7.38 – 7.34 (m, 2H), 7.27 –7.21 (m, 1H), 7.12-7.05 (m, 3H), 2.65 (s, 3H).

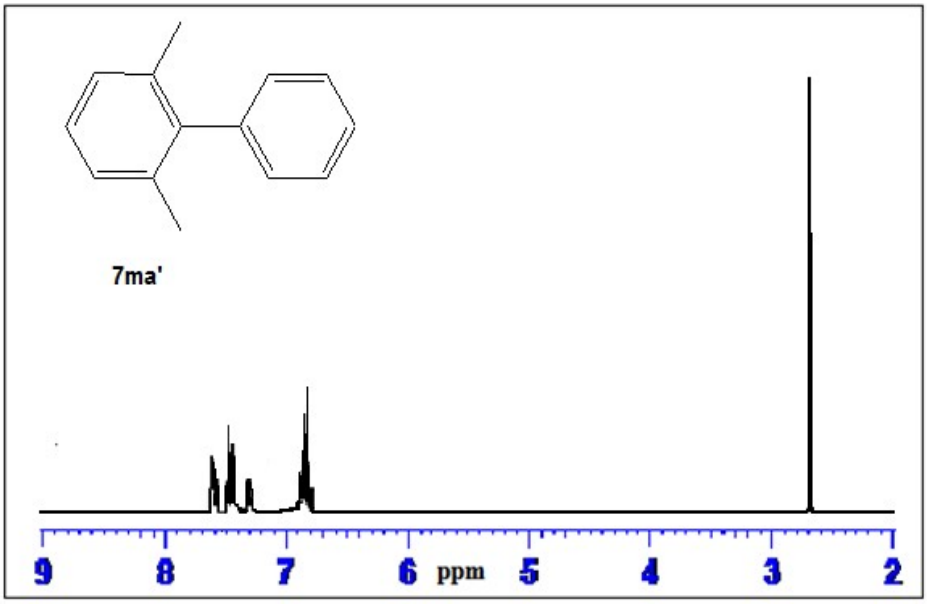


Figure 6.16. ^{1}H NMR (400MHz, $CDCl_3$) of 2,3-dimethylbiphenyl (7ka'):δ 7.62 – 7.58 (m, 2H), 7.49 – 7.39 (m, 2H), 7.29 –7.25 (m, 1H), 6.90-6.78 (m, 3H), 2.65 (s, 6H).

6.4. Conclusion

In summary, a new Pd(II)-complex [κ^3-*N*, *N*′, *O*-Pd(1⊂2)H_2O]OAc (4) was synthesized from the ligand, 1⊂2 (3) with partially encapsulated 2,6-diaminopyridine in the hydrophobic β-cyclodextrin cavity in ChCD (1). Due to the partial inclusion, the $–NH_2$ groups of 2,6-diaminopyridine can act as coordination sites in the ligand (3). The compounds including the complex (4) were characterized by various spectroscopic and physicochemical methods and the data suggests the complex (4) to have square planner geometry. The presence of β-cyclodextrin moiety in the Pd-complex makes it highly water soluble. Therefore, the catalytic activity of the Pd-complex for Suzuki reaction in aqueous media has been explored. The complex showed high catalytic activities and affords good to excellent yields for the coupled products in respective reactions with various substrates. As compared to some palladium catalyzed recations in aqueous media,[39,40] this catalyst works effectivelly for water insoluble arylhalides in Suzuki reacton in terms of lesser recation time, lower temparature (ambient temparature) and optimum load bereft of any phase transfer catalyst and organic solvents. Also it's easy recyclability and easy recovery from aqueous phase makes the catalyst environmentally benign, sustainable and cost-effective.

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