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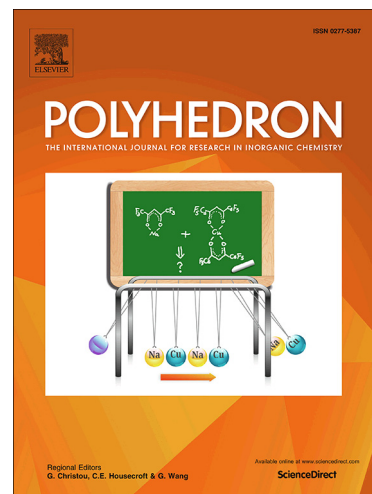
Bidentate organochalcogen ligands (N, E; E = S / Se) as stabilizers for recyclable palladium nanoparticles and their application in Suzuki-Miyaura coupling reactions

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Abstract

Chalcogen-substituted secondary amines **L1** and **L2** have been synthesized by the reduction of corresponding imines. Ligands **L1** and **L2** have been characterized using ^{1}H and ^{13}C{^{1}H} NMR spectroscopy. The Schiff base precursors used for the synthesis of **L1** has also been characterized using single crystal diffraction. Both the ligands (**L1** and **L2**) have been used as stabilizers for palladium nanoparticles (PdNPs) **1−4** in two different ratios of Pd:**L** (1:1 and 1:4). The NPs have been characterized by UV-Visible spectroscopy, powder X-ray diffraction, Scanning Electron Microscopy (SEM), SEM-EDX, and Transmission Electron Microscopy (TEM). The chalcogen donor site showed remarkable role in the stabilizing these nanoparticles. The Pd:**L** ratio in NPs has been noticed to affect the size and shape of particles and also their catalytic behavior. Size of the NPs has been found to be in a range of NPs **1**: 2−3; NPs **2**: 4−5; NPs **3**: 3−4; NPs **4**: 4−6 nm. When explored as catalyst, the low loading of these NPs gave significant conversions for the coupling of various aryl halides with phenylboronic acid (Suzuki-Miyaura coupling) in a short reaction time of 3 h. The highest catalytic activity has

been observed for Pd NPs **1** (Pd:**L** ratio 1:1) due to the uniformity in the dispersion of NPs. The distinct advantage associated with these NPs (**1−4**) is that they retain catalytic activity after the reaction and are recyclable up to three times. Attempts were made to gain mechanistic insights of catalysis and it was found that both homogeneous and heterogeneous catalytic process contributes to the catalysis.

Keywords: Organochalcogen, Stabilizer, Nanoparticles, Suzuki-Miyaura Coupling (SMC), Catalysis.

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1. Introduction

Palladium-catalyzed Suzuki-Miyaura coupling (SMC) reactions have been used as cutting edge technology [1−3] for many years by chemists. The coupled product of SMC, biaryl derivatives, have been reported to be the part of natural products, pharmaceutical ingredients, agrochemicals and several organic motifs used in material science [4]. SMC has also been considered very important owing to the mild reaction conditions and easy availability of boronic acid derivatives [4(a),5]. The less hazardous and non-toxic nature of organoborane, their easy handling and removal of boron-containing by-products in comparison to that of other organometallic reagents is an additional advantage [5,6]. The most common metal used for catalysing SMC is palladium which has been used either in the form of molecular Pd(II) complex or as nano-sized Pd(0) species [7]. It is believed that real catalytic species is palladium(0) which could be molecular Pd(0) or nanosized palladium species and molecular Pd(II) complexes act only as the dispensers of these species [8]. In case of nanocatalysts, surface area and morphology are important parameters for catalytic performance of

palladium NPs when they are used as catalysts or formed in situ during the course of the reaction. The high surface to volume ratio and uniformity in distribution of NPs are expected to enhance the catalytic activity [9].

The synthesis of well defined and mono-dispersed Pd NPs of small size without compromising significantly with the catalytic activity continues to be a challenge. The protecting reagent of NPs should be designed in a way that the activity loss of synthesized NPs is minimal. The ligands used to protect PdNPs result in the reduction of their catalytic activity. Therefore, the role of ligand is very crucial as it determines the dispersion of the NPs and affects their catalytic efficiency, recyclability, composition, solubility, and size [10]. Various agents such as dendrimers, organic ligands, oganofluorous compounds, ionic liquids, and surfactants have been reported to stabilize metal NPs [7,11,12]. Many of such chemicals including the organophosphorus ones have been reported to be toxic [13]. Presence of a functional group like thiol, amine, carbonyl or hydroxyl in a stabilizer significantly affects the activity [10] of NPs and sometimes diminishes the activity due to strong chemisorptions. Organochalcogen ligands have emerged as a new family of air as well as moisture stable building blocks for molecular catalysts [14−24]. For example, alkyl thiolates have been widely utilized as a stabilizer for designing catalytically active Pd, Pt and Au NPs [12,25,26]. A few examples have also been repored on the use of thioethers (which are soft donors, less toxic and easy to handle in the air) to design catalytically active metal NPs [21,26]. Thioether functional group inhibits strong chemisorption to the metal surface and inturn the resulting metal NPs have significant activity [26]. Moreover, the presence of hard donor site (such as amine) in combination with chalcogenoether ligand may render an alteration in the stabilization efficiency. The stabilizing tendency of a chalcogenoether with secondary amine donor group is not yet explored. Thus, herein we are reporting N

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and S/Se donor site containing organic ligand for the stabilization of PdNPs with different metal to ligand ratio (Pd:L). The catalytic activity and recyclability of these NPs has been tested for SMC reaction of aryl chloride and aryl bromides.

2. Experimental

2.1. Starting materials

Thiophenol, diphenyl diselenide, benzene-1,4-carbaldehyde, $NaBH_4$, sodium tetrachloropalladate, potassium carbonate, cesium carbonate, phenylboronic acid, and all aryl halides were procured from Aldrich (USA). Commercially available reagents were used as received without further purification. All catalytic reactions were carried out in glassware dried in an oven under ambient conditions. Organochalcogen amine was synthesized under N_2 atmosphere. Commercial nitrogen gas was passed successively through traps containing solutions of alkaline anthraquinone-sodium dithionite, alkaline pyrogallol, concentrated H_2SO_4 and KOH pellets before use. A nitrogen atmosphere was created using Schlenk techniques.

2.2. Physical measurement

The ^1H, $^{13}C\{^1H\}$, DEPT-135 NMR and $^{77}Se\{^1H\}$ spectra were recorded on a Bruker Spectrospin DPX-300 NMR spectrometer at 300.13, 75.47 and 57.24 MHz respectively. The internal standard was tetramethylsilane while recording proton and carbon-13 NMR spectra, whereas it was Me_2Se in case of Se-77 NMR spectrum. The chemical shifts are reported in ppm. ^{13}C DEPT NMR was used routinely to determine the number of hydrogen atoms linked to carbon atoms. Single-crystal structure data were collected with a Bruker AXS SMART Apex CCD diffractometer using Mo Kα (0.71073 Å) radiation at 298(2) K. The software SADABS was used for absorption correction (if needed) and SHELXTL for space group, structure determination, and refinements. Hydrogen atoms were included in idealized positions with isotropic

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thermal parameters set at 1.2 times that of the carbon atom to which they were attached in all cases. TEM studies were carried out with a Technai G^2 20 electron microscope operated at 200 kV to study the nature of nanoparticles. The specimens for TEM were prepared by dispersing the powdered solid in ethanol by ultrasonic treatment, dropping slurry onto a porous carbon film supported on a copper grid and then drying it in air. Carl Zeiss EVO5O scanning electron microscope (SEM) associated with an EDX system model QuanTax 200, based on the SDD technology and giving an energy resolution of 127 eV at Mn-Kα, was used to observe phase morphologies of the nanoparticles. The samples for SEM were mounted on a circular metallic sample holder with sticky carbon tape and scanned in different regions in order to minimize the error in the analysis made for evaluating the morphological parameters. Powder X-ray diffraction (PXRD) studies were carried out on a Bruker D8 Advance diffractometer with Ni-filtered Cu$K\alpha$ radiation using a scan speed of 1s and scan step of 0.02°. Shimadzu UV probe UV2450 spectrophotometer has been used to record UV-Vis spectra. Melting points of ligands were determined in an open capillary sealed at one end, with an apparatus equipped with electric heating and reported as such. The products of catalytic reactions were separated and purified (if required) by chromatography using silica gel (60−120 mesh) column. *n*-Hexane and its mixtures with chloroform/ethyl acetate in variable proportions were used as eluent. The products were authenticated by matching their NMR data with those reported in the literature. Atomic absorption spectrophotometer (AAS), Lab India AAS 7000 was used to determine Pd content in NPs. The 10, 20 and 30 ppm solutions of Pd(II) prepared from Na$_2$PdCl$_4$ in deionized water were used as standard. Total Sulphur content was determined using XOS Sindie 7039 (M Series) Benchtop Sulphur MWD XRF Analyzer.

2.3. *Preparation of Schiff bases* **L1'** *and* **L2'**

A mixture of 3-(phenylsulfanyl)propylamine (0.835 g, 5 mmol) / 3-(phenylselanyl)propylamine (1.07 g, 5 mmol) and terepthaldehyde (0.335 g, 2.5 mmol) in ethanol was refluxed at 70 °C for 8h. The reaction mixture was then cooled in the refrigerator to get a precipitate of product. The precipitate was filtered off and washed with cold ethanol (2 × 5 mL). The resulted schiff bases (**L1′**and **L2′**) were finally dried in *vacuo*.

L1′: White Solid. Yield: 0.354 g (82%). ^{1}H NMR (300 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 2.08 (q, 4H, H$_3$), 3.03 (t, J= 7.2 Hz, 4H, H$_2$), 3.76 (t, J = 6.6 Hz, 4H, H$_4$), 7.14−7.18 (m, 2H, H$_{SPh}$), 7.24−7.29 (m, 4H, H$_{SPh}$), 7.34−7.36 (m, 4H, H$_{SPh}$), 7.76 (s, 4H, H$_5$), 8.30 (s, 2H, H$_1$). ^{13}C{^{1}H} NMR (75 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 30.1, 31.2, 59.8, 125.8, 128.3, 128.8, 129.1, 136.5, 138.0, 161.0.

L2′: Light Yellow Solid. Yield: 0.459 g (87%) ^{1}H NMR (300 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 2.16 (q, 4H, H$_3$), 3.03 (t, 4H, H$_2$), 3.75 (t, J = 6.3 Hz, 4H, H$_4$), 7.25−7.28 (m, 6H, H$_{SePh}$), 7.51−7.54 (m, 4H, H$_{SePh}$), 7.77 (s, 4H, H$_5$), 8.29 (s, 2H, H$_1$). ^{13}C{^{1}H} NMR (75 MHz): δ (ppm) 25.4 (CH$_2$), 31.0 (CH$_2$), 60.7, 126.7, 128.2, 129.0, 132.4, 137.9, 161.0. ^{77}Se{^{1}H} NMR (57 MHz, CDCl$_3$, 25 °C, Me$_2$Se): δ (ppm) 287.2

2.4. *Reduction of Schiff bases and synthesis of* **L1** *and* **L2**

Schiff base **L1′**/**L2′** was dissolved in ethanol (**L1′**; 0.864 g, 2.0 mmol / **L2′**; 1.056 g, 2.0 mmol). Thereafter, the ethanolic solution of NaBH$_4$ (0.098 g, 2.5 mmol) was added to the reaction mixture and stirred at room temperature for 12 h. The solvent was evaporated off under reduced pressure on a rotary evaporator. The resulting product was mixed with water and extracted using EtOAc (2 × 50 mL). The organic layer was washed with water (3 × 50 mL) and dried over anhydrous sodium sulfate.

L1: White solid. Yield: 0.286 g (66%). ^{1}H NMR (300 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 1.85 (q, *J = 7.2 Hz,* 4H, H$_3$), 2.74 (t, *J* = 6.9 Hz, 4H, H$_2$), 2.99 (t, *J* = 7.5 Hz, 4H, H$_4$), 3.75 (s, 4H, H$_1$), 7.16−7.19 (m, 2H, H$_{SPh}$), 7.25−7.29 (m, 8H, H$_{SPh}$), 7.32−7.34 (m, 4H, H$_5$).^{13}C{^{1}H} NMR (75 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 29.4, 31.4, 47.9, 53.5, 125.7, 128.0, 128.7, 128.9, 136.5, 138.9.

L2: White Solid. Yield: 0.385 g (73%). ^{1}H NMR (300 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 1.87 (q, *J = 7.2 Hz,* 4H, H$_3$), 2.68 (t, *J* = 6.9 Hz, 4H, H$_2$), 2.92 (t, *J* = 7.2 Hz, 4H, H$_4$), 3.69 (s, 4H, H$_1$), 7.19−7.21 (m, 10H, H$_{SePh}$), 7.45−7.47 (m, 4H, H$_5$). ^{13}C{^{1}H} NMR (75 MHz, CDCl$_3$, 25 °C, TMS): δ (ppm) 25.3 (CH$_2$), 30.2 (CH$_2$), 48.6, 53.3, 126.5, 127.9, 128.8, 130.2, 132.2, 138.7. ^{77}Se{^{1}H} NMR (57 MHz, CDCl$_3$, 25 °C, Me$_2$Se): δ (ppm) 292.3.

2.5. *Synthesis of Pd nanoparticles 1−4*

The Na$_2$[PdCl$_4$] (0.147 g, 0.5 mmol) for **1** and **3** / (0.074 g, 0.25 mmol) for **2** and **4** was dissolved in 50 mL of methanol. The solution of ligand **L1** [0.218 g, 0.5 mmol] / **L2** [0.265 g, 0.5 mmol] (Pd:**L1** = 1:1) for **1** and **3**; 1.0 mmol of **L1** (0.436 g)/**L2** (0.530 g) for **2** and **4** (Pd:**L1** = 1:4) made in 100 mL of mixture of chloroform and hexane (equal volume of each) was added to it with vigorous stirring. Then, the solution of NaBH$_4$ [0.058 g (1.5 mmol) for **1** and **3** / 0.024 g (0.75 mmol) for **2** and **4**] in methanol was added dropwise to the reaction mixture with stirring over a period of 30 min. The mixture was allowed to stir further for 6 h. On the completion of the reaction, the solvent in the mixture was reduced to 10 mL on a rotary evaporator. The resulting residue was centrifuged, washed with methanol (3 × 30 mL) and dried in *vacuo*.

2.6. *General procedure for Suzuki-Miyaura C-C coupling reactions using nanoparticles 1-4 as a catalyst*

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An oven-dried round bottom flask was charged with aryl halide (1 mmol), phenylboronic acid (1.2 mmol), K_2CO_3 (2 mmol), DMF/H_2O (3 mL/1 mL) and nanoparticles (3 mg, 0.1 mol% of Pd). The reaction mixture was heated on an oil bath, and the temperature was maintained at 100 °C. On the completion of the reaction, the product was extracted with 10 mL of diethyl ether. The extract was washed with water (3 × 10 mL) and dried over anhydrous Na_2SO_4. The solvent of the extract was evaporated off and the residue was subjected to NMR. Column chromatography was used for further purification on silica gel using chloroform and hexane mixture (5:95% to 15:85%) as eluent. The solvents were recovered for safe disposal.

2.7. Catalytic recyclability of NPs after separation

The coupling reaction of 4-bromobenzaldehyde with phenylboronic acid was carried out with NPs **1** (0.1 mol% of Pd) under optimal reaction condition. After completion of the reaction, ethyl acetate and water were added to the reaction mixture and it was centrifuged. Aqueous and organic layers were decanted off and black residue left was washed thoroughly with ethyl acetate and water to remove organic content and base respectively. The resulting residue was dried in *vacuo*. The organic layer, which was separated after standard workup procedure, was subjected to ^{1}H NMR for estimating conversion. The NPs separated were reused for the next catalytic cycle using optimized procedure. The protocol was repeated three times and results are given in Table 3.

2.8. Hg poisoning test

A mixture of NPs **1** (0.5 mol % of Pd) and elemental Hg (Pd:Hg::1:400) was taken in a reaction flask and stirred at room temperature for 10 minutes before the addition of coupling reactants. Thereafter, 4-bromobenzaldehyde (1.0 mmol), phenylboronic acid (1.2 mmol), K_2CO_3 (2 mmol), and aqueous DMF (3+1 mL) was added and the reaction

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was carried out at 100 °C. The yield of the expected product (4-formybiphenyl) was only 87% after 6 h. The Hg was recovered and stored safely.

2.9. PPh₃ poisoning test

A mixture of NPs **1** (0.5 mol% of Pd) and triphenylphosphine (Pd: PPh₃::1:5) were taken in an oven dried round bottom flask and stirred for 10 minutes prior to the addition of the reactants.Thereafter, 4-bromobenzaldehyde (1.0 mmol), phenylboronic acid (1.1 mmol), K_2CO_3 (2.0 mmol) and aqueous DMF (1+3 mL) were added and the reaction was carried out at 100 ºC. The conversion obtained was 88%.

2.10. Two-phase test

A mixture of 4-bromobenzoic acid-immobilized silica (0.20 g), prepared by reported procedure, [27] phenylboronic acid (0.36 g, 3 mmol), 4-bromoacetophenone, and K_2CO_3 (0.56 g, 4 mmol) were heated at 100 °C for 12 h in DMF / water (6 mL / 3 mL) mixture in the presence of **1** (1 mol% of Pd). After completion of the reaction, it was cooled and filtered through a G-4 crucible. The residue left over crucible was washed with 30 mL of water followed by diethyl ether (40 mL). The filtrate and washings were collected together and extracted with 30 mL of diethyl ether. The solvent of the extract was evaporated off on rotary evaporator and the residue subjected to ^{1}H NMR. The residue in G-4 crucible was hydrolyzed with KOH (1.68 g dissolved in 10 mL of EtOH + 5 mL of H_2O) at 90 °C for 3 days. After this, it was neutralized with aqueous 20% (v/v) HCl and extracted with dichloromethane (20 mL) followed by ethyl acetate (30 mL). The organic phases were combined together and its solvent was evaporated off. The resulting residue was analyzed with ^{1}H NMR.

2.11. Hot filtration test

This test was carried out using 4-bromobenzaldehyde (1 mmol), phenylboronic acid (1.1 mmol) in the presence of NPs **1** under optimum reactions conditions. After 10

minutes of reaction, the hot reaction mixture was filtered through G4 crucible containing celite. Half of the reaction mixture was quenched and the product conversion was monitored by ^{1}H NMR. The other half of reaction mixture was further stirred for additional 5 h, and then the product conversion was then the conversion was estimated using ^{1}H NMR. The cross coupled product was obtained in 8% and 26% after 10 minutes and 5 h of reaction respectively.

3. Results and discussion

3.1.   General

The syntheses of **L1**, **L2** and Pd nanoparticles **1−4** stabilized with these ligands have been summarised in Scheme 1. The **L1** and **L2** are white solids whereas NPs are in the form of black powder. The NPs and ligands, both, are stable under ambient conditions and can be stored for several months.
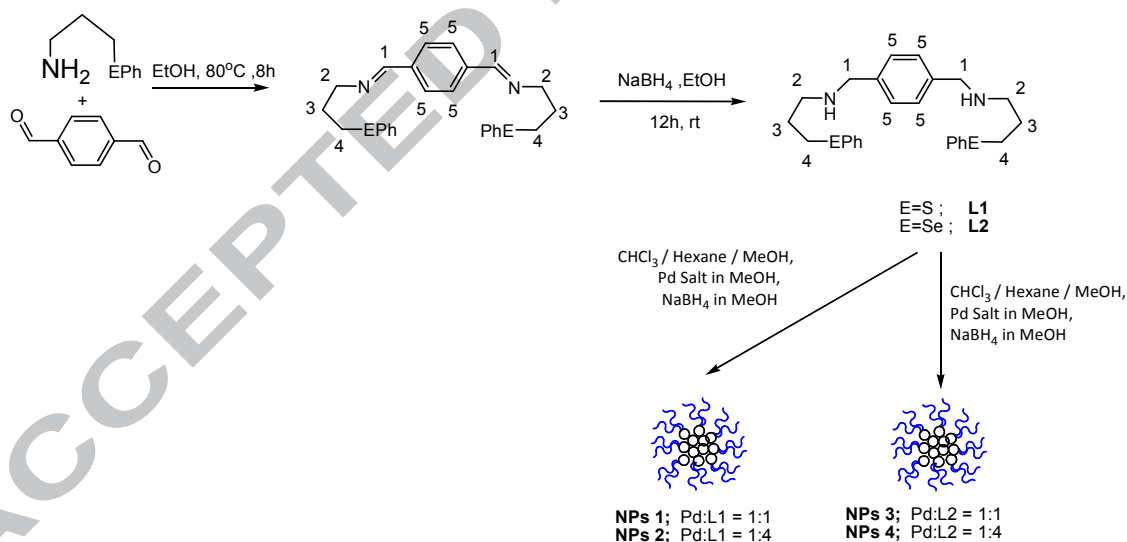
**Scheme 1.** Synthesis of **L1-L2** and NPs **1-4**

L1/L2 has a solubility in common organic solvents such as CHCl$_3$, CH$_2$Cl$_2$, CH$_3$CN, C$_2$H$_5$OH and diethyl ether. Pd NPs are soluble in CHCl$_3$ and can be easily dispersed in EtOH.

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3.2. Crystal structure

The crystal structure of the ligand precursor (**L1′**) has been determined with X-ray diffraction on their single crystals. Crystals were obtained by slow evaporation of its solution made in EtOH. The loan pair on NH and CH of imine group adopt a trans conformation. The bond angles C(4)−N(1)−C(5) and N(1)−C(4)−C(2) are 117.8(2)° and 124.5(3)° which indicates the slightly distorted trigonal planer enviorment. The bond angle C(8)−S(1)−C(7) was found to be 103.20(13)°, indicating the distorted tetrahedral geormetry around S. The S−C bond lengths are consistent with reported value for Schiff bases of 1′-hydroxy-2′-acetonaphthone [18]. The C−H·····π and N−H·····H−C secondary interaction resulted in the formation of two dimentional structure (Fig. S1; Supplementary data).
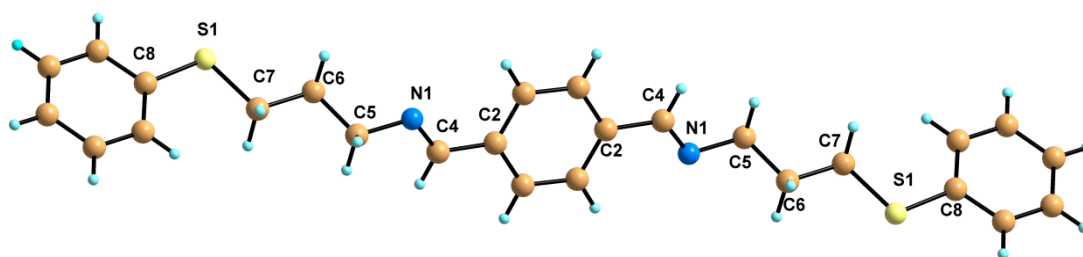
Fig. 1. ORTEP diagram of **L1′** with 50% probability ellipsoids; selected bond lengths (Å): S(1)−C(8) 1.753(3), N(1)−C(5) 1.453(3), N(1)−C(4) 1.251(3), S(1)−C(7) 1.799(3); selected bond angles (°): C(4)−N(1)−C(5) 117.8(2)°, N(1)−C(4)−C(2) 124.5(3)°, C(8)−S(1)−C(7) 103.20(13)°.

3.3. NMR spectra

The ^1H and $^{13}C\{^1H\}$ NMR spectra of **L1** and **L2** were found to be consistent with their molecular structures. In ^1H NMR spectrum of **L1′**, the peak of CH=N was observed at 8.30 ppm (Fig. S2). After reduction of **L1′** with $NaBH_4$ to **L1**, this peak became shielded by 4.56 ppm and appeared at 3.75 ppm (Fig. S5). In the same way, a signal of CH=N carbon in $^{13}C\{^1H\}$ NMR spectrum appeared at 161 ppm in **L1′** (Fig. S3) and became shielded by 107.5 ppm when finding at 53.5 ppm in **L1** (Fig. S6). In case of **L2′**, the signal at 8.29 ppm in ^1H NMR (Fig. S8) and 161.0 ppm in $^{13}C\{^1H\}$ NMR are

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the characteristic peaks of CH=N (Fig. S9). After reduction, the signals of corresponding protons and carbon get shielded by 4.6 and 107.7 ppm respectively and appear at 3.69 in ^{1}H NMR (Fig. S12), and 53.3 ppm in ^{13}C{^{1}H} NMR spectrum (Fig. S13). The peak in ^{77}Se{^{1}H} NMR in **L2** which appear at 292.3 ppm (Fig. S15) was deshielded by 5.1 ppm with respect to 287.2 ppm of **L2′** (Fig. S11). For **L1** and **L2**, the signal for N−H proton was observed at 1.418 ppm and 1.256 ppm respectively.

3.4. Characterization of palladium-chalcogen NPs 1−4

Black powder was subjected to PXRD, SEM, SEM-EDX, UV, and HR-TEM characterization techniques. Powder X-ray diffraction (PXRD) pattern of **1** and **3** showed a peak at 40.0 (2θ) corresponding to (111) plane of Pd(0) (d ~ 2.26). HR-TEM studies indicate that black powder is made of highly uniform and mono-dispersed nanosized particles which are spherical in shape.

(a)   (b)

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(c)   (d)
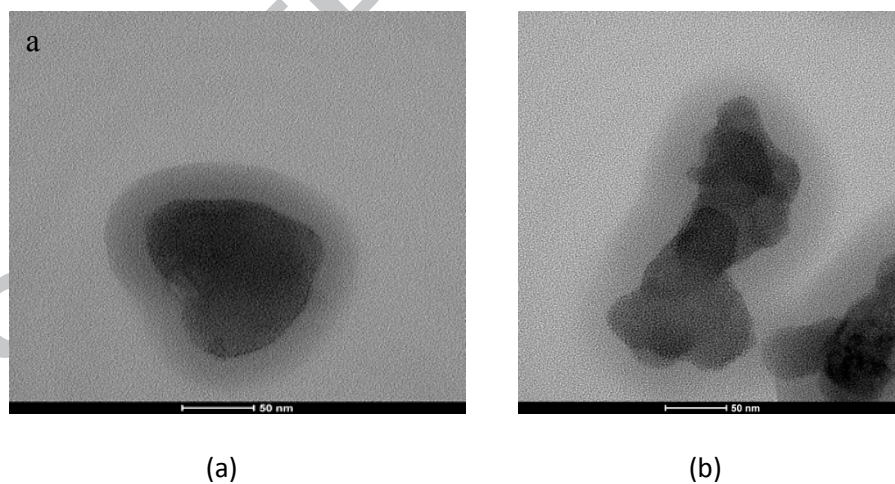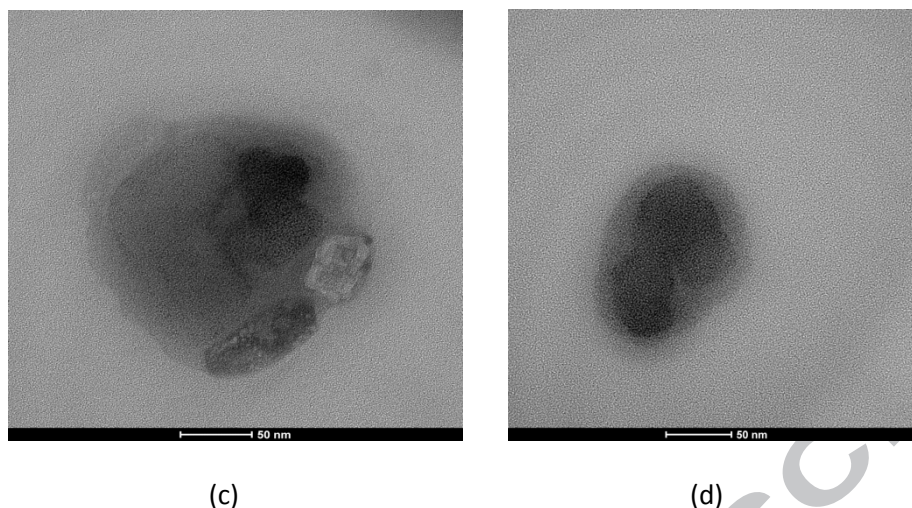
Fig. 2. HRTEM Images of Nanoparticles at scale bar 50 nm (a) **1**, (b) **2**, (c) **3**, (d) **4**

The size of NPs have been found to be in the range of **1**: 2−3 nm; **2**: 4−5 nm; **3**: 3−4 nm; **5**: 4−6 nm.

The EDX (SEM) (Fig. S20−S23) has revealed that the NPs are composed of palladium and organochalcogen fragments. The atomic weight % ratio of Pd:S in nanoparticles **1** and **2** is 37:63 and 38:61, while in case of **3** and **4**, the Pd:Se ratio 37:63 and 36:64 respectively. During the reduction of Pd(II) salt, it is completely converted into Pd(0) as revealed by the UV-Vis spectrum. The appearance of the peak around 260 nm [28] in the UV-Vis spectrum of a solution of each type of NPs indicates the presence of Pd(0) in the solution (Fig. 3). Simultaneously, the absence of peak for Pd(II)/[PdCl$_4$]$^{2-}$ in these NPs suggests complete conversion.

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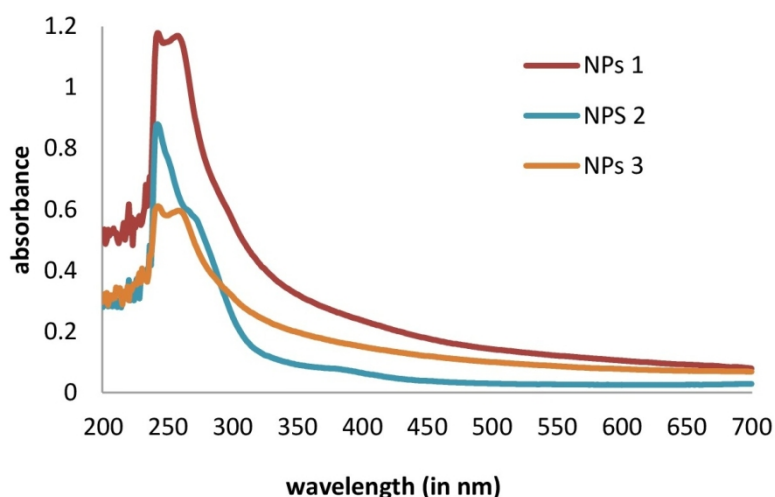
Fig. 3. UV-Vis spectrum of NPs **1−3**

3.5. ***Applications of NPs as catalysts in Suzuki−Miyaura C−C coupling reaction***
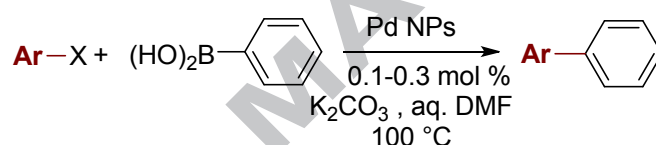
Scheme 2. Suzuki-Miyaura coupling for C−C bond formation

Suzuki-Miyaura coupling reactions (Scheme 2) have been carried out using nanoparticles **1−4** as a catalyst. The reaction conditions were optimized using **1** as a catalyst for which 4-bromobenzaldehyde was reacted with phenylboronic acid in presence of different bases and solvents at 100 °C. The yield of coupled product was found to be maximum in the presence of NPs **1** (loading equal to 0.1 mol% of Pd) when K_2CO_3 was used as a base (Table 1; Entry 5). However, with other bases like KOH and $CsCO_3$, the yield was relatively lower (Table 1; Entry 1, 2). The yield of coupled product was negligible when Et_3N was used as a base (Table 1; Entry 3). Among the solvents optimized, the best result was given by aqueous DMF (Table 1; Entry 4). Highly polar solvents like DMSO or DMF when used without water, reduces the yield significantly (Table 1; Entry 5, 7). The reaction did not occur when THF (Table 1; Entry 6) was used as a solvent.

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Table 1 Optimization of reaction conditions

$$Br{-}C_6H_4{-}CHO \quad + \quad PhB(OH)_2 \quad \rightarrow \quad Ph{-}C_6H_4{-}CHO$$

Entry No.	Solvent	Base	Yield (%)^b
1	DMF+Water	Cs$_2$CO$_3$	85
2	DMF+Water	KOH	70
3	DMF+Water	NEt$_3$	trace
4	DMF+Water	K$_2$CO$_3$	≥99
5	DMF	K$_2$CO$_3$	81
6	THF	K$_2$CO$_3$	trace
7	DMSO	K$_2$CO$_3$	78

Reaction conditions: 1 mmol of 4-bromobenzaldehyde, 1.2 mmol of phenylboronic acid, 2 mmol of the base, 4 mL of solvent, the temperature of bath 100 °C, 0.1 mol% of **1**, reaction time was 3 h. ^{b}NMR Yield.

Detailed results of Suzuki-miyaura coupling of different aryl halides including aryl chlorides using nanoparticles **1−4** as a catalyst are summarised in Table 2. PdNPs stabilized by organoselenium ligands were less active than those of organosulphur ligands (Table 2; Entry 5). The catalytic performance of all four NPs was the same in case of 4-bromobenzaldehyde (Table 2; Entry 5). The difference in activity of nanoparticles **1−4** was observed when deactivated aryl halides were used as a coupling partner. The reaction of 4-bromoanisole gave the cross-coupled product in ≥99% yield in presence of **1** (0.1 mol%) (Table 2; Entry 8) but only 70% in the presence of **2** (0.3 mol%) (Table 2; Entry 8). The yield of cross coupled product decreased significantly when **3** (0.3 mol% of Pd) was used as catalyst (Table 1; Entry 4). Catalyst **4** was found to be ineffective for coupling of this substrate even at higher loading (0.8 mol% of Pd) (Table 2; Entry 8). Catalysts **1** and **2** show good results with bromobenzene (Table 2; Entry 6) as yield of the biaryl was 90% and 85.% were obtained in 3 hours of reaction time. 2-Chlorobenzaldehyde was converted to the cross-coupled product in 82% yield using **1** as catalyst in 3h of reaction time (Table 2; Entry 1). However, the yield was only 58% in presence of **2** when the reaction was carried out for 20 h (Table 2; Entry 1). 4-

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Chlorobenzaldehyde gave ≥99% and 80 % with **1** and **2** respectively (Table 2; Entry 3). When the coupling of 4-chlorobenzoic acid was carried out with phenylbroronic acid, **>99%** yield was obatined in the presence of both **1** and **2** (Table 2; Entry 4). A 45% conversion of chlorobenzene into cross cross coupled was obtained when **1** was used as catalyst. However in the preseence of **2**, the yield of cross coupled product was negligible (Table 2; Entry 2). The high catalytic activity of organosulphur ligand stabilized NPs was also observed for aryl chlorides for which organoselenium stabilized PdNPs were ineffective. This may be due to the presence of a combination of borderline sigma donor S and hard donor site (i.e. N) in the ligand, which can create a balance in the stabilization in NPs. However, the electron donating ability of Se is relatively lower than S, which may decrease the catalytic performance of **3** and **4** for aryl chloride substrates in SMC.

Table 2 Suzuki Miyaura C−C coupling reactions catalyzed with Pd NPs^a **2–4**

$$Ar-X \quad + \quad PhB(OH)_2 \quad \rightarrow \quad Ph-Ar$$

Entry No.	Aryl halide	**1**		**2**		**3**		**4**	
		t (h)	Yield^b	t (h)	Yield^b	t (h)	Yield^b	t (h)	Yield^b
1	2-Chlorobenzaldehyde	3	82	20	58	20	–	–	–
2	Chlorobenzene	3	45	20	–	24	Trace	–	–
3	4-Chlorobenzaldehyde	3	>99	3	80	3	–	–	–
4	4-Chlorobenzoic acid	3	>99	2	>99	2	–	–	–
5	4-Bromobenzaldehyde	3	>99	3	>99	3	>99	3	85
6	Bromobenze	3	90	3	85	3	trace	12	10mg99
7^c	4-Brmobenzonitrile	4	91	4	–	5	5mg40	5	5mg50
8^c	4-Bromoanisole	~3	>99	3	70	4	35	5	trace

^{a}Reaction conditions: ArX (1 mmol), phenyl boronic acid (1.2 mmol), K_2CO_3 (2 mmol), $DMF+H_2O$ (3+1)mL, temperature of bath 100 °C, amount of **1** and **3** equivalent to 0.1 mol% of palladium, amount of **2** and **4** equivalent to 0.3 mol% of palladium, ^{b}NMR % Yield. ^{c}Amount of catalyst equivalent to 0.3 and 0.8 mol% of palladium for **3** and **4** respectivelly.

To test the recyclability of these NPs, a coupling reaction between 4-bromobenzaldehyde and phenyl boronic acid was carried out with NPs **1** under optimal reaction conditions. Results have been summerized in Table 3 indicate that

the NPs are active up to three catalytic cycles. For the coupling of 4-bromobenzaldehyde under standered reaction conditions, the cross coupled product was obtained in ≥99% yield for the first cycle (Table 3; Entry 1). However, the catalytic performance was significantely reduced and and cross-coupled product was obtaned in 61% and 41% yield for second and third cycle respectively. The catalytic activity gets reduced after consecutive cycles because of the possibility of agglomeration, leaching and poisoning of catalyst.

**Table 3** Recyclability of NPs **1** in Suzuki Miyaura coupling reaction[a]

$$Br{-}C_6H_4{-}CHO \quad + \quad PhB(OH)_2 \quad \rightarrow \quad Ph{-}C_6H_4{-}CHO$$

Entry No.	Aryl bromide		Reaction Cycle		
			I	**II**	**III**
1	4-Bromobenzaldehyde	t (h)	5	5	5
		Yield[b]	~100	60	41

[a]Reaction conditions: 1.0 mmol of 4-bromobenzaldehde, 1.2 mmol of phenylboronic acid and 2 mmol of K_2CO_3, 3 mL of aq. DMF, temperature of bath 100 °C. [b]%NMR yield. Catalyst amount 0.1 mol% of palladium.

To establish the nature of catalysis by NPs **1−4** (i.e. homogeneous vs heterogeneous), mercury poisoning and two-phase tests were performed. For mercury poisoning test, the coupling of 4-bromobenzaldehyde was carried out in the presence of **1** (loading equal to 0.1 mol% of Pd). After a reaction time of 12 h, the yield of the cross-coupled product was 87%. Thus, the catalytic activity of NPs has been found to be diminished to some extent. As Pd NPs are protected with ligand molecules, the possibility of the heterogeneous pathway cannot be presumed. It can also be considered that the presence of both hard and soft binding sites in ligand may not allow the Pd atoms to escape and get poisoned easily. However, mercury poisoning test alone is insufficient to conclude about the nature or type of catalytic process. Thus, a two phase test (Scheme 3) was carried out to ascertain the contributions of heterogeneous and homogeneous catalytic processes [29-30]. This

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test provides an idea about catalytically active metal species.
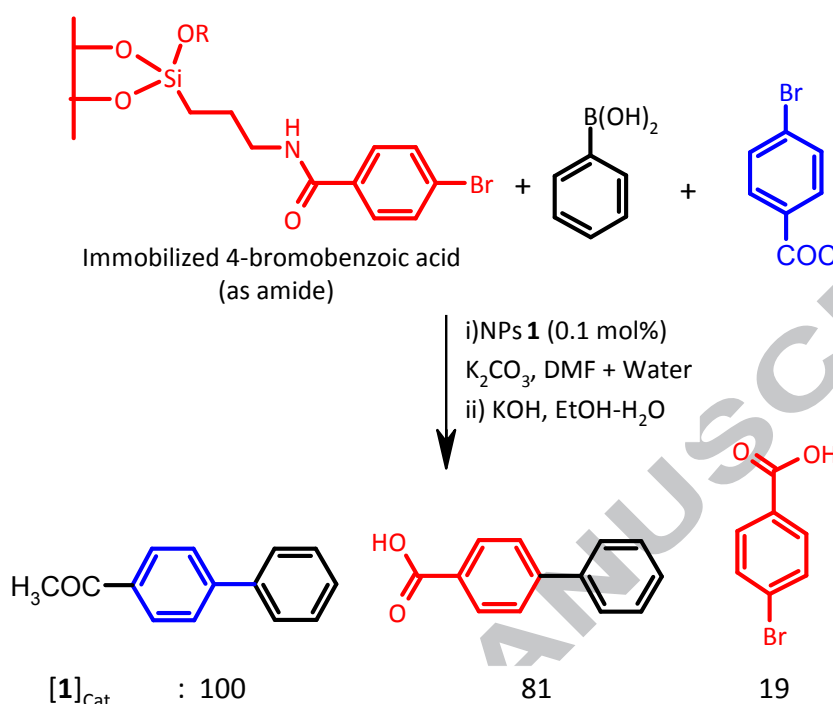
Scheme 3 Two phase test in the presence of **1** and **3**

In this test, which was developed by Rebek and co-workers, [29] one of the coupling partners (aryl halide) is heterogenized and the second partner (phenylboronic acid) along with another aryl halide (homogeneous) have been reacted in the presence of a catalyst under optimum reaction conditions. If the catalyst behaves in a heterogeneous manner, the supported aryl halide is not expected to get converted to a coupled product. However, if palladium(0) is being released into solution, the supporting substrate is likely to get converted into the product. Thus 4-bromobenzoic acid immobilized silica was reacted with phenylboronic acid in the presence of 4-bromoacetophenone under optimum reaction conditions using **1** as a catalyst (Scheme 3). After 12 h of reaction time, the soluble part was separated and analyzed with ^{1}H NMR. The yield of the cross-coupled product (4-acetyl biphenyl) was ≥99%. The solid phase separated through G-4 crucible was hydrolyzed, and the resulting residue after workup was analyzed

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with ^{1}H NMR. The conversion of immobilized 4-bromobenzoic to 4-bromobenzoic and biphenyl-4-carboxylic acid was observed 19% and 81% respectively. It appears that reaction is catalyzed with Pd species homogeneously as well as heterogeneously. However, the contribution of homogeneous catalysis is higher. These results suggested that some of the catalytically active palladium(0) leached from palladium NPs and is responsible for homogeneous catalysis. In order to understand the homogeneous catalysis with palladium, hot filtration test was performed. Half part of the reaction mixture was hot filtered through G-4 crucible after 10 minutes of the reaction and the other half was quenched and subjected to ^{1}H NMR. The former part was stirred for 5 hours and subjected to ^{1}H NMR. The yield of the cross-coupled product was 8% and 26% in case of 10 minutes and 5 hours respectively. This suggests that a small fraction of Pd(0) leaches out as nanoparticles are efficiently stabilized by the ligands which was responsible for the conversion. However, reaction proceeds with slow rate. The total sulphur content was also analysed in a mixture of NPs and DMF using XOS Sindie 7039 (M Series) Benchtop Sulphur MWD XRF Analyzer. Similar analysis was made for the reaction mixture of Suzuki coupling after completion of reaction. The level of sulphur content observed for DMF, mixture of NPs in DMF, and catalytic reaction mixture were nearly same. Therefore, it indicates that almost insignificant amount of sulphur leaches out from the NPs into the solution during the course of Suzuki coupling.

The plausible mechanism for the Suzuki Miyaura coupling catalysed by Pd(0) NPs is given in Fig. 4 and is consistent with the earlier reports [21, 26(b), 31, 32]. It is based on the assumption that the Pd(0) nanoparticles are well protected by the ligand and do not allow Hg/PPh$_3$ to reach the surface in order to poison the catalyst at a high rate. Some Pd(0) atoms can leach out in the solution from the nanoparticles

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and involve in oxidative addition to initiate the catalytic cycle. This contributed to the homogeneous mode of reaction which is supported by hot filtration and two phase test. On the other hand, reaction proceeds via heterogeneous pathway and some part of the reaction occurs on the surface of the catalyst. Thus the present coupling reaction is purely neither homogeneous nor heterogeneous. Rather, it is a cocktail type catalysis wherein both modes contribute to the catalysis.
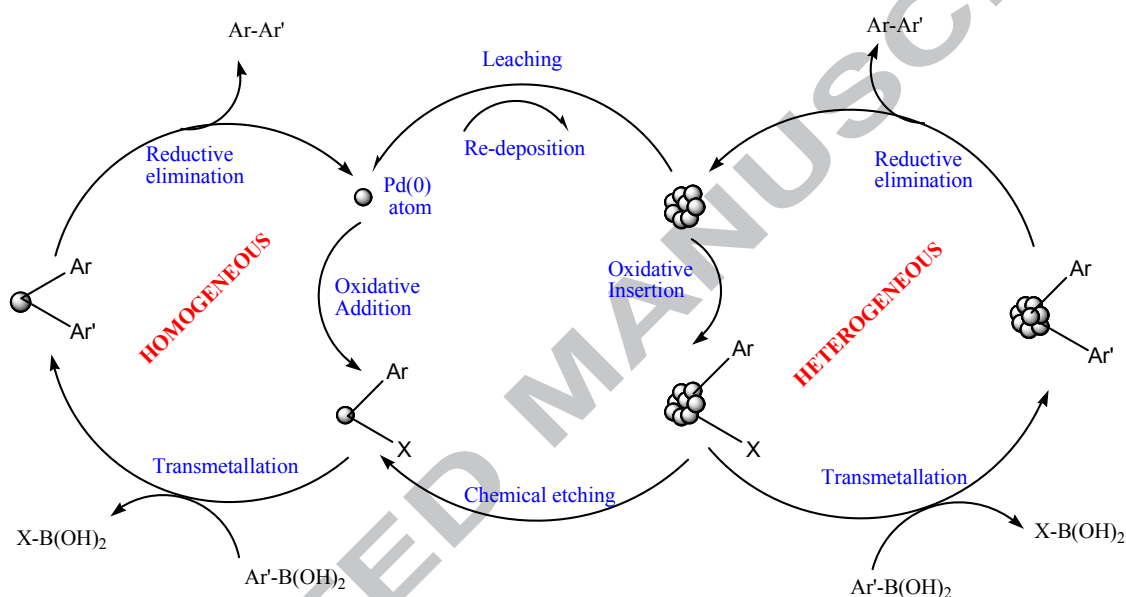
Fig. 4. Proposed mechanism for Pd(0) NPs catalyzed Suzuki coupling reaction

4. Conclusions

L1 and **L2** have been synthesized. Palladium NPs **1−4** have been synthesized using **L1** and **L2** as a stabilizer which are supposed to be moisture and air insensitive than conventional phosphorus analogs. The difference in Pd:**L** ratio affects the size, shape, and dispersion of NPs and also their catalytic activity. The size of PdNPs was found to be **1**: 2-3; **2**: 4-5; **3**: 3-4; **4**: 4-6 nm. The NPs show good catalytic efficiency for Suzuki-Miyaura coupling (SMC) of various aryl halides including aryl chlorides with phenylboronic acid at low catalyst loading (0.1−0.3 mol % of Pd). The cross coupled products were obtained in good yield for aryl halides in a short reaction time of 3 h.

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The distinct advantage associated with the NPs **1−4** is that they remain catalytically active after the first reaction cycle and can be recycled up to three times. The highest catalytic activity was observed for **1** probably due to the appropriate size, dispersion and combination of donor sites in stabilizer. Two-phase test, conducted in the presence of **1**, suggested the contribution of homogeneous as well as heterogeneous Pd species in the catalytic processes.

Acknowledgement

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