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An efficient and recoverable palladium organocatalyst for Suzuki reaction in aqueous media

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Meso-tetrakis[4-(methoxycarbonyl)phenyl]porphyrinatopalladium(II) as a palladium organocatalyst was synthesized and then used in aqueous media as a heterogeneous organocatalyst in Suzuki reaction. The prepared organocatalyst was characterized using UV–visible, infrared and NMR spectroscopies. It was found to be an efficient catalyst for Suzuki coupling reaction between phenylboronic acid and a broad range of aryl halides. Mild reaction conditions, water solvent as green media, and easy catalyst separation and reusability are the advantages of the presented method.

KEYWORDS

cross-coupling reaction, heterogeneous catalyst, organocatalyst, reusable, water media

1 | INTRODUCTION

Palladium-catalysed cross-coupling reactions such as the Suzuki,[1] Heck,[2] Stille,[3] Kumada,[4] Negishi[5] and Hiyama[6] reactions have revolutionized the chemical industry related to the synthesis of various natural products and agrochemicals, and medicinal and supramolecular chemistry.[7] Among the various cross-coupling methods that are available, the Suzuki reaction is one of the most efficient for the synthesis of unsymmetric biaryls Ar—Ar from aryl halides Ar—X (X = I, Br, Cl) and arylboronic acids Ar—$B(OH)_2$.[8] This reaction is one of the most extensively studied in organic chemistry due to its operational simplicity, easy accessibility, excellent functional group tolerance and the environmentally friendly properties of the starting reagents, which are some of the key factors responsible for increased research into this particular reaction.[9]

Generally, the Suzuki cross-coupling reaction is frequently performed in the presence of a palladium catalyst containing well-designed ligands based on phosphine, which can facilitate the corresponding transformation efficiently.[10] However, phosphine ligands are sensitive to air and/or moisture, expensive and toxic. In the past few decades extensive efforts have been made to develop palladium catalysts that utilize inexpensive phosphine-free ligands such as thiol,[11] imidazole,[12] carbocyclic,[13] anionic carbocyclic,[14] N-heterocyclic carbene[15] and porphyrin ligands.[16] Among these phosphine-free ligands, porphyrins have been recognized as efficient and suitable organocatalyst ligands for palladium species, due to simple preparation, non-toxicity and versatility of their steric and electronic properties. In the last decade, some palladium porphyrins have been developed and widely studied for C—C coupling reactions. In 2007, Kostas and coworkers reported the successful synthesis of a water-soluble palladium complex with a porphyrin ligand for the Suzuki reaction.[17] Wan and Liu also reported an ionic palladium porphyrin, which showed high activity in the Heck coupling reaction.[18] Although these homogeneous palladium porphyrin catalysts have contributed to modified catalytic activity significantly as a result of electron-donating functionality, they often suffer from problems of separation of these expensive catalysts after reactions have completed. Furthermore, these homogeneous catalysts often result in heavy metal contamination of the desired isolated products.

In order to overcome the problems mentioned above, immobilization of homogeneous palladium porphyrins onto solid supports has been extensively employed in the field of Suzuki coupling reactions, since immobilized palladium porphyrin catalysts have the fewer of the drawbacks of homogeneous catalysts, such as the difficulties in recovery and regeneration. In recent years, many types of carriers, such as mesoporous silica[16] and ion exchange resins,[19] have been applied to support palladium porphyrin catalysts. However, a substantial decrease in activity and selectivity of the

immobilized catalysts is frequently observed, since there are a number of challenges and obstacles such as leaching of palladium species from the supports, easy agglomeration of palladium particles and low utilization efficiency of palladium. Thus, it is desirable to develop more efficient and simple heterogeneous palladium porphyrin catalysts for Suzuki coupling reactions.[20]

Various strategies should be considered to overcome the general problems of Suzuki reaction catalysts (like difficult separation, moisture and air sensitivity, non-recyclability and non-environmentally friendly conditions). Regarding reaction media, water is not only non-toxic, inexpensive and safe,[21] but most Suzuki products are insoluble in water, and thus this can be a suitable factor for the easy separation of products from reactants by simple extraction and, more importantly, separation and recovery of catalyst can be easy. During our work on carbon–carbon coupling reactions,[22] the idea of using water as a green solvent encouraged us to design a new air- and moisture-stable palladium organocatalyst, namely meso-tetrakis[4-(methoxycarbonyl) phenyl]porphyrinatopalladium(II), [Pd-TMCPP], that can be applied as a heterogeneous and recyclable catalyst in aqueous media for Suzuki cross-coupling reaction.

2 | EXPERIMENTAL

2.1 | General methods

All solvents and chemicals were of reagent grade quality and were purchased commercially and used without further purification. Fourier transform infrared (FT-IR) spectra were recorded with a Nicolet Magna 550 spectrometer. UV–visible spectra were recorded using a GBC cintra-6 UV–visible spectrophotometer. NMR spectra were recorded with a Bruker DPX-400 MHz spectrometer using $CDCl_3$ and DMSO-d_6 as solvents. Elemental analyses (C, H, N) were conducted using a Carlo Erba EA 1108 analyser. Melting points were determined with a Stuart Scientific SMP2 apparatus and are uncorrected. The amount of Pd leached in the catalytic reaction was determined using a inductively coupled plasma (ICP) analysis (Perkin-Elmer instrument).

2.2 | Palladium organocatalyst preparation

2.2.1 | Synthesis of organic ligand

Meso-tetrakis[4-(methoxycarbonyl)phenyl]porphyrin, [H_2TMCPP], was synthesized according to the following procedure.[23] Freshly distilled pyrrole (1.4 ml, 20 mmol) was added to a mixture of 4-formylmethylbenzoate (3.42 g, 20 mmol) and nitrobenzene (15 ml). The mixture was refluxed for 4 h in the presence of propionic acid (70 ml) and then cooled to room temperature. The purple crystals of the porphyrin were filtered, washed with distilled water and dried in an oven at 80 °C. Yield 20.4% (0.9 g). ^{1}H NMR (400 MHz, DMSO-d_6, δ, ppm): 8.85 (s, 8H, β-hydrogen pyrrolic), 8.47 (d, 8H, aromatic), 8.32 (d, 8H, aromatic), 4.14 (s, 12H, OCH_3), −2.77 (s, 2H, pyrrolic hydrogens). FT-IR (cm^{-1}): 3310 (N─H), 2944 (C─H, sp^3), 1722 (C═O), 1604 (C═N), 1275 (C─N). UV–visible (DMF, nm): 419 (Soret band), 519, 554, 598 and 653 (Q bands).

2.2.2 | Synthesis of palladium–porphyrin complex (organocatalyst)

The [Pd-TMCPP] organocatalyst was prepared by refluxing [H_2TMCPP] (0.30 g, 0.354 mmol) and $PdCl_2$ (0.135 g, 0.763 mmol) in DMF (100 ml) for 12 h. The purification of [Pd-TMCPP] was performed by repeated recrystallization and precipitation from DMF–H_2O solutions. Yield 86.1% (0.29 g). ^{1}H NMR (400 MHz, DMSO-d_6, δ, ppm): 8.86 (s, 8H, β-hydrogens pyrrolic), 8.47 (d, 8H, aromatic), 8.32 (d, 8H, aromatic), 4.11 (s, 12H, OCH_3). FT-IR (cm^{-1}): 2944 (C─H, sp^3), 1724 (C═O), 1607 (C═N), 1275 (C─N). UV–visible (DMF, nm): 416 (Soret band), 527 and 562 (Q bands).

2.3 | Spectroscopic and physical data

4-Methoxy-1,1′-biphenyl (**3a**). M.p. 87–89 °C. FT-IR (KBr, ν, cm^{-1}): 3060, 3055, 2959, 1605, 1485, 1249, 1036. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 3.85 (3H, s), 6.98 (2H, d, J = 8.4 Hz), 7.30 (1H, t, J = 7.2 Hz), 7.42 (2H, t, J = *7.6 Hz*), 7.55 (4H, t, J = 7.6 Hz). Anal. Calcd for $C_{13}H_{12}O$ (%): C, 84.75; H, 6.57. Found (%): C, 83.56; H, 5.86.

2-Methoxy-1,1′-biphenyl (**3b**). M.p. oil. FT-IR (KBr, ν, cm^{-1}): 3059, 2932, 1597, 1481, 1259, 1028. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 3.78 (3H, s), 6.98 (1H, d, J = 8.8 Hz), 7.02 (1H, t, J = 8.8 Hz), 7.28–7.33 (3H, m), 7.40 (2H, t, J = 7.2 Hz), 7.53 (2H, d, J = 5.2 Hz). Anal. Calcd for $C_{13}H_{12}O$ (%): C, 84.75; H, 6.57. Found (%): C, 82.95; H, 5.66.

4-Phenylphenol (**3c**). M.p. 156–159 °C. FT-IR (KBr, ν, cm^{-1}): 3406, 3036, 1603, 1486. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 6.93 (2H, d, J = 8.4 Hz), 7.33 (1H, t, J = 7.2 Hz), 7.44 (2H, t, J = 7.6 Hz), 7.51 (2H, d, J = 8.4 Hz), 7.56 (2H, t, J = 7.2 Hz), 8.28 (1H, d, J = 6.8 Hz). Anal. Calcd for $C_{12}H_{10}O$ (%): C, 84.68; H, 5.92. Found (%): C, 83.95; H, 5.66.

1,1′-Biphenyl (**3d**). M.p. 68–69 °C. FT-IR (KBr, ν, cm^{-1}): 3033, 1567, 1477. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.33–7.38 (2H, m), 7.45 (4H, t, J = 7.2 Hz), 7.61 (4H, d, J = 8 Hz). Anal. Calcd for $C_{12}H_{10}$ (%): C, 93.46; H, 6.54. Found (%): C, 92.75; H, 5.86.

4-Nitro-1,1′-biphenyl (**3e**). M.p. 107–109 °C. FT-IR (KBr, ν, cm^{-1}): 3098, 1597, 1513, 1476, 1344. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.46–7.53 (3H, m), 7.64 (2H, d, J = 6.8 Hz), 7.75 (2H, d, J = 8.8 Hz), 8.31 (2H, d, J = 6.8 Hz). Anal. Calcd for $C_{12}H_9NO_2$ (%): C, 72.35; H, 4.55; N, 7.03. Found (%): C, 71.18; H, 4.66; N, 6.44.

2-Hydroxy-5-phenylbenzaldehyde (**3f**). M.p. 96–99 °C. FT-IR (KBr, ν, cm^{-1}): 3419, 3043, 2856, 1673, 1603, 1465. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 6.94 (1H, d, J = 8.8 Hz), 7.54 (2H, t, J = 7.6 Hz), 7.63 (2H, m), 7.70

(1H, d, J = 2.8 Hz), 8.26 (1H, d, J = 1.2 Hz), 8.29 (1H, d, J = 1.2 Hz), 10.96 (1H, s). Anal. Calcd for $C_{13}H_{10}O_2$ (%): C, 78.77; H, 5.09. Found (%): C, 77.97; H, 4.76.

1,4-Diphenylbenzene (**3 g**). M.p. 189–192 °C. FT-IR (KBr, ν, cm^{-1}): 3030, 1621, 1461. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.27–7.31 (2H, m), 7.39 (4H, t, J = 7.6 Hz), 7.57 (4H, d, J = 7.2 Hz), 7.61 (4H, s). Anal. Calcd for $C_{18}H_{14}$ (%): C, 93.87; H, 6.13. Found (%): C, 92.97; H, 5.36.

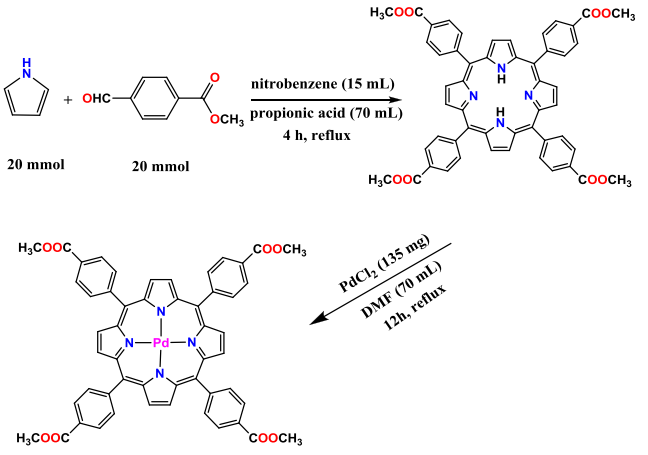
5-Phenylnicotinic acid (**3 h**). M.p. 252–254 °C. FT-IR (KBr, ν, cm^{-1}): 3431, 3076, 1676, 1603, 1442. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.51 (3H, t, J = 7.6 Hz), 7.59 (2H, t, J = 7.6 Hz), 7.69 (1H, s), 8.23 (1H, s), 8.25 (1H, s). Anal. Calcd for $C_{12}H_9NO_2$ (%): C, 72.35; H, 4.55; N, 7.03. Found (%): C, 71.97; H, 4.36; N, 6.98.

3-Phenylbenzaldehyde (**3i**). M.p. oil. FT-IR (KBr, ν, cm^{-1}): 3060, 2826, 2728, 1697, 1594, 1476. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.41–7.45 (1H, m), 7.48–7.52 (2H, m), 7.63 (2H, d, J = 7.2 Hz), 7.66 (1H, t, J = 1.6 Hz), 7.87–7.89 (2H, dd, J = 6.4 Hz), 8.13 (1H, s), 10.11 (1H, s). Anal. Calcd for $C_{13}H_{10}O$ (%): C, 85.69; H, 5.53. Found (%): C, 85.17; H, 4.96.

4-Phenylbenzaldehyde (**3j**). M.p. 56–58 °C. FT-IR (KBr, ν, cm^{-1}): 3066, 1710, 1588, 1476, 765, 691. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.45 (1H, t, J = 6.8 Hz), 7.53 (2H, t, J = 7.1 Hz), 7.77 (2H, d, J = 7.8 Hz), 7.91 (2H, d, J = 7.8 Hz), 7.99 (2H, d, J = 8.2 Hz), 10.06 (1H, s, CHO). Anal. Calcd for $C_{13}H_{10}O$ (%): C, 85.69; H, 5.53. Found (%): C, 84.67; H, 4.76.

Quaterphenyl (**3 k**). M.p. 298–300 °C. FT-IR (KBr, ν, cm^{-1}): 3031, 1620, 1479. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.36–7.40 (2H, m), 7.48 (4H, t, J = 7.2 Hz), 7.66 (4H, d, J = 9.2 Hz), 7.70 (8H, s). Anal. Calcd for $C_{24}H_{18}$ (%): C, 94.08; H, 5.92. Found (%): C, 93.17; H, 4.76.

2-Hydroxy-3,5-diphenylbenzaldehyde (**3 l**). M.p. 114–116 °C. FT-IR (KBr, ν, cm^{-1}): 3426, 3047, 2848, 1651, 1607, 1459. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 7.38–7.44 (2H, m), 7.46–7.50 (4H, m), 7.59–7.67 (4H, m), 7.78 (1H, d, J = 2.4 Hz), 7.88 (1H, d, J = 2.4 Hz), 10.05 (1H, s), 11.52 (1H, s). Anal. Calcd for $C_{19}H_{14}O_2$ (%): C, 83.19; H, 5.14. Found (%): C, 83.01; H, 4.96.



SCHEME 1 Synthetic pathway for preparation of catalyst

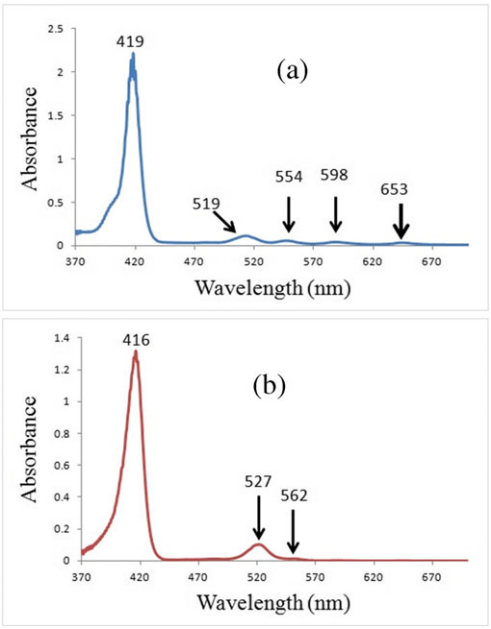


FIGURE 1 UV–visible spectra of (a) [H_2TMCPP] and (b) [Pd-TMCPP]

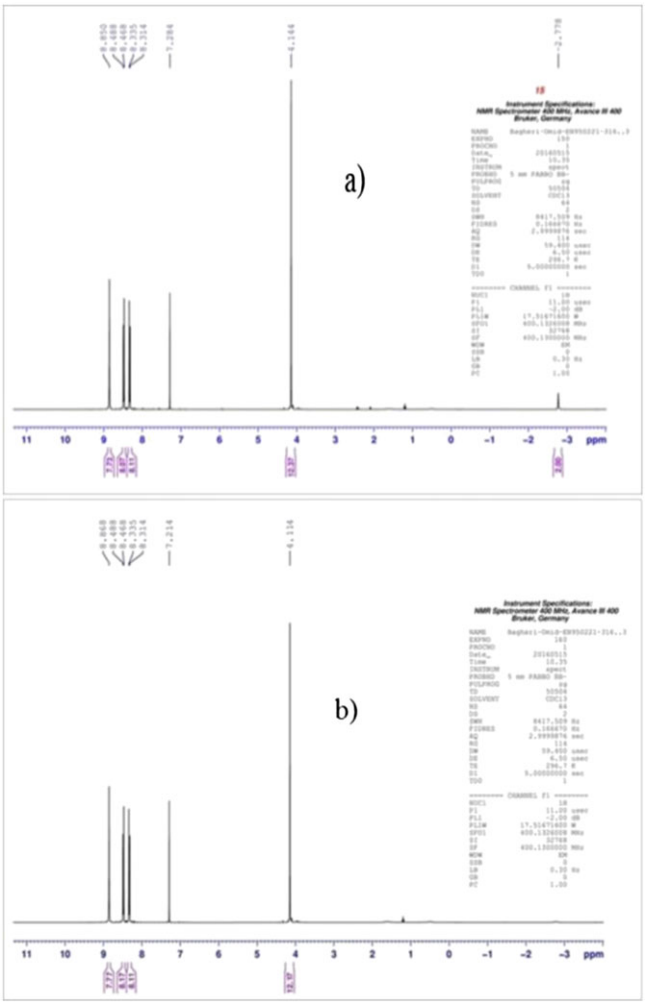


FIGURE 2 ^1H NMR spectra of (a) [H_2TMCPP] and (b) [Pd-TMCPP]

(4-Hydroxy-[1,1′-biphenyl]-3,5-diyl)dimethanol (**3 m**). M.p. 90–93 °C. FT-IR (KBr, ν, cm^{-1}): 3412, 3028, 1601, 1480. ^1H NMR (400 MHz, CDCl3, δ, ppm): 4.90 (2H, s), 5.23 (2H, s), 7.13 (1H, s), 7.44 (2H, t, J = 7.2 Hz), 7.49 (1H, s), 7.54 (2H, t, J = 7.6 Hz), 7.93 (1H, s), 7.95 (1H, s). Anal. Calcd for $C_{14}H_{14}O_3$ (%): C, 73.03; H, 6.13. Found (%): C, 72.17; H, 5.36.

4,4′-Dimethyl-1,1′-biphenyl (**3n**). M.p. 119–122 °C. FT-IR (KBr, ν, cm^{-1}): 3043, 3019, 2957, 1602, 1488. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 2.33 (6H, s), 7.12 (4H, d, J = 6.2 Hz), 7.40 (4H, d, J = 6.2 Hz).

4-(4-Methoxyphenyl)pyridine (**3o**). M.p. 93–95 °C. FT-IR (KBr, ν, cm^{-1}): 3045, 2956, 1610, 1480, 1252, 1040. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 3.87 (3H, s), 7.00 (2H, d, J = 8.3 Hz), 7.50 (2H, d, J = 5.4 Hz), 7.62 (2H, d, J = 8.3 Hz), 8.62 (2H, d, J = 5.4 Hz).

2-(4-Methoxyphenyl)thiophene (**3p**). M.p. 104–106 °C. FT-IR (KBr, ν, cm^{-1}): 3001, 2967, 2841, 1606, 1500, 1430, 1298, 1250, 1188, 1029, 824, 701. ^1H NMR (400 MHz, $CDCl_3$, δ, ppm): 3.83 (3H, s), 6.90–7.06 (3H, m), 7.20–7.26 (2H, m), 7.53 (2H, d, J = 4.7 Hz).

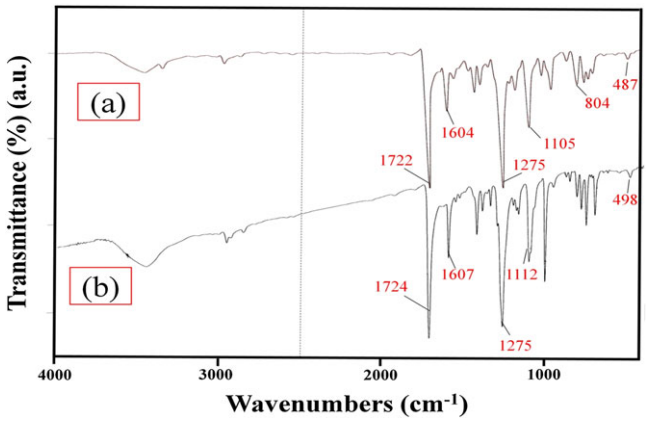


FIGURE 3 FT-IR spectra of (a) [H_2TMCPP] and (b) [Pd-TMCPP]

3 | RESULTS AND DISCUSSION

3.1 | Characterization of palladium organocatalyst

The synthetic route for the preparation of the catalyst is shown in Scheme 1. During the synthesis of [Pd-TMCPP], the initial UV–visible absorption bands at 419, 519, 554, 598 and 653 nm (Figure 1a) are shifted and disappear and new bands appear at 416 (Soret band), 527 and 562 nm (Q bands) (Figure 1b) in DMF solution, indicating that palladium ion is inserted into the porphyrin ring.

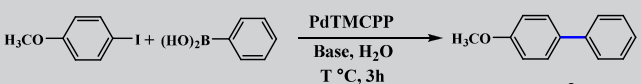
Furthermore, the ^1H NMR spectra confirm the UV–visible spectral data. In the ^1H NMR spectrum of [H_2TMCPP] (Figure 2a) in DMSO-d_6, the signal at −2.77 ppm corresponds to pyrrolic hydrogens. In the spectrum of [Pd-TMCPP] (Figure 2b), the mentioned signal is absent, which confirms the synthesis and metallation of porphyrin.

In addition, FT-IR spectroscopy was applied for the characterization of porphyrin and Pd–porphyrin. As shown in Figure 3, the FT-IR absorption bands are different for porphyrin and Pd–porphyrin complex. It is seen that the N—H bond stretching and bending frequencies of the porphyrin ligand are located at *ca* 3300 and 960 cm^{-1}. While, when the palladium ion is inserted into the porphyrin ring, the N—H bond vibration band of the porphyrin ligand disappears and the characteristic band of Pd—N bond appears at *ca* 1000 cm^{-1} which indicates the formation of the Pd–porphyrin complex.[24] The bands at 1722 and 1604 cm^{-1} are assigned to carbonyl of ester and C═N, respectively.

3.2 | Suzuki cross-coupling reaction in presence of palladium organocatalyst

Optimization of the reaction parameters is one of the most important factors for catalytic reactions, for instance optimization of type of base, temperature and amount of catalyst.

TABLE 1 Optimization of [Pd-TMCPP]-catalysed Suzuki reaction between 4-iodoanisole and phenylboronic acid[a]



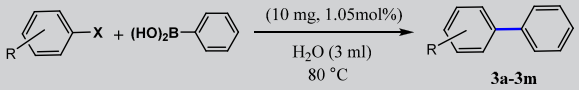
1a 2 3a

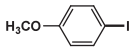
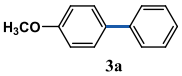
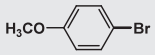
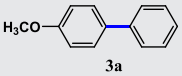
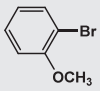
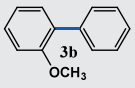
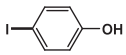
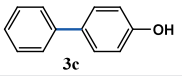
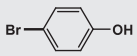
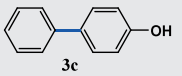
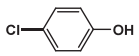
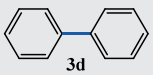
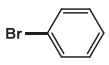
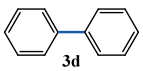
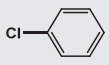
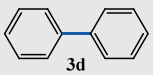
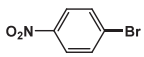
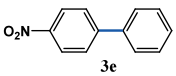
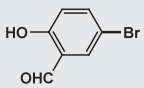
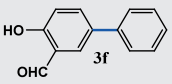
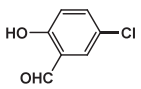
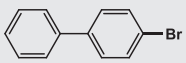
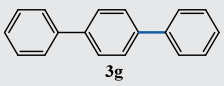
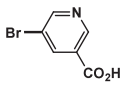
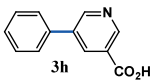
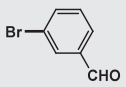
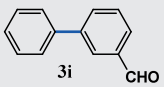
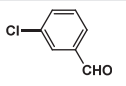
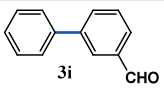
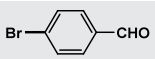
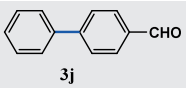
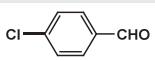
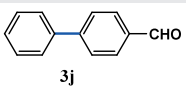
Entry	Base	Solvent	Catalyst, mg (mmol)	Temp. (°C)	Yield (%)[b]
1	K_2CO_3	H_2O	5 (0.00525)	80	70
2	**K_2CO_3**	**H_2O**	**10 (0.0105)**	**80**	**95**
3	K_2CO_3	H_2O	15 (0.01575)	80	96
5	K_2CO_3	H_2O	10 (0.0105)	r.t.	48
6	K_2CO_3	H_2O	10 (0.0105)	reflux	96
7	Na_2CO_3	H_2O	10 (0.0105)	80	65
8	K_3PO_4	H_2O	10 (0.0105)	80	68
9	NEt_3	H_2O	10 (0.0105)	80	42

[a]Reaction conditions: 1a (1 mmol), 2 (1.1 mmol), base (1.5 mmol), H_2O (3 ml).

[b]Isolated yield.

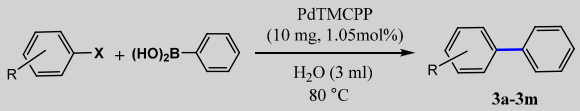
TABLE 2 Suzuki reaction of various aryl halides with phenylboronic acid in the presence of [Pd-TMCPP][a]

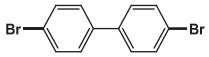
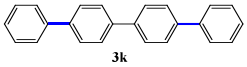
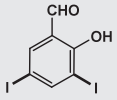
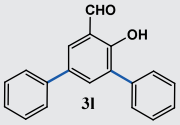
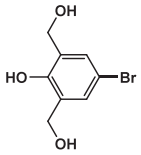
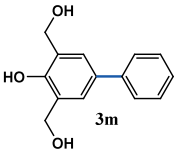
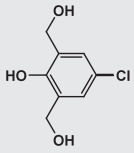
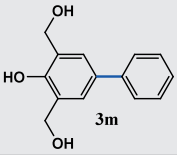


Entry	Reactant	Product	Time (min)	Yield (%)[b]
1			180	95
2			200	93
3			200	90
4			210	87
5			180	94
6			220	91
7			280	89
8			200	94
9			220	92
10			300	88
11			240	89
12			240	93
13			290	87
14			230	90
15			280	91
16			250	91
17			320	89
18			260	94
19			300	87

(*Continues*)

TABLE 2 (Continued)



Entry	Reactant	Product	Time (min)	Yield (%)[b]
20		 3k	240	90
21		 3l	230	95
22		 3m	270	92
23		 3m	350	89

[a]General reaction conditions: aryl halide (1 mmol), phenylboronic acid (1.1 mmol), base (1.5 mmol), H_2O (3 ml).

[b]Isolated yield.

From academic as well as industrial viewpoints, alternative reaction conditions are of considerable interest given an increasing emphasis on making this palladium-catalysed cross-coupling process 'greener',[25] for instance by minimizing the use of organic solvents.[26] Water is the best candidate in this regard, because of its low cost, non-toxicity and non-flammability and its being of low environmental concern.[27] Based on the advantages of water and the fact that [Pd-TMCPP] is insoluble in water, in this work water was selected as a green solvent. Therefore, the reaction between 4-iodoanisole (1 mmol) and phenylboronic acid (1.1 mmol) in the presence of 3 ml of water was selected as a model reaction and the progress of the reaction was monitored by TLC. The effects of amount of catalyst, temperature and role of various bases like Na_3PO_4, K_2CO_3, Na_2CO_3 and NEt_3 were investigated. Various amounts of catalyst between 5 and 15 mg were further investigated for this reaction and 10 mg of catalyst (1.05 mol% Pd) is found to be optimal. For higher amounts of catalyst, the desired product is obtained in nearly quantitative yield (Table 1, entries 1–3). This coupling reaction is found to be highly sensitive to the reaction temperature (Table 1, entries 2, 5 and 6). A temperature of 80 °C is found to be optimal for the model reaction. Among the bases, K_2CO_3 shows the best performance among organic and inorganic bases (Table 1, entries 2 and 7–9).

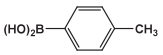
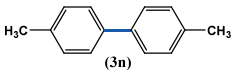
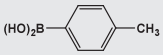
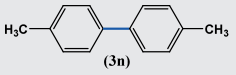
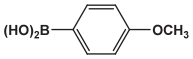
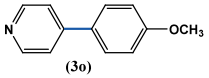
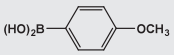
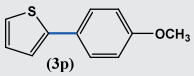
After optimization of reaction conditions, other aryl halides were investigated under these optimized conditions (Table 2). It is observed that the organocatalyst is efficient for various aryl halides (X = Cl, Br, I) with both electron-donating groups (entries 1–7, 22, 23) and electron-withdrawing groups (entries 11, 15–20). First of all, the reactions of aryl iodides were investigated, and good yields are achieved. Compared with aryl iodide, a lower yield of products is obtained when employing aryl bromides as substrates. This lower yield should be attributed to the fact that the oxidation–addition step is slower for aryl bromide in comparison with aryl iodide. In the presence of aryl chloride, the reactivity is lower than that for iodo and bromo counterparts. Good efficiencies are observed in the presence of bihalide substrates (entries 20, 21). Furthermore, this methodology is applicable to heterocyclic substrates, as demonstrated by using 5-bromonicotinic acid (entry 15) under the optimized conditions, producing compound **3 h** in 91% yield.

In addition, various arylboronic acids were surveyed for investigation of generality and versatility of the prepared catalyst (Table 3). As evident from Table 3, the final products **3n–3p** are obtained in excellent yields. Heterocyclic substrates such as pyridine and thiophene can be successfully applied in the present methodology.

3.3 | Reusability and stability of palladium organocatalyst

Reusability of a catalyst is the most important factor in catalysis reactions. To investigate the reusability of the palladium organocatalyst, the Suzuki reaction was performed under the optimum reaction conditions involving 4-iodoanisole (1 mmol), phenylboronic acid

TABLE 3 Synthesis of various biphenyl (biheterocyclic phenyl) products using various substituted phenylboronic acids in the presence of [Pd-TMCPP][a]

Entry	Aryl halide	Arylboronic acid	Product	Time (min)	Yield (%)[b]
1	4-Iodotoluene		 (3n)	180	96
2	4-Bromotoluene		 (3n)	300	93
3	4-Bromopyridine		 (3o)	360	91
4	2-Iodothiophene		 (3p)	270	93

[a]General reaction conditions: aryl halide (1 mmol), arylboronic acid (1.1 mmol), base (1.5 mmol), H_2O (3 ml).

[b]Isolated yield.

TABLE 4 Reusability of [Pd-TMCPP] catalyst in Suzuki reaction[a]

Entry	Yield (%)[b]	Pd leached (%)[c]
1	95	0.56
2	95	0.53
3	93	—
4	91	—
5	87	1.02

[a]Reaction conditions: 4-iodoanisole (1 mmol), phenylboronic acid (1.1 mmol), K_2CO_3 (1.5 mmol), H_2O (3 ml), 80 °C, 180 min.

[b]Isolated yield.

[c]Determined by ICP analysis.

(1.1 mmol), K_2CO_3 (1.5 mmol) and [Pd-TMCPP] (1.05 mol% Pd) in water (3 ml) at 80 °C under air. The desired product was obtained in 95% yield after 180 min. Because [Pd-TMCPP] is a heterogeneous catalyst in water media, it can be easily separated from the reaction mixture. At the end of each reaction, the [Pd-TMCPP] catalyst was isolated by simple filtration, washed exhaustively with deionized water and ethyl acetate and dried at 80 °C under reduced pressure for 12 h before being reused with fresh 4-iodoanisole and phenylboronic acid. The catalyst can be reused five times without any reduction in its catalytic activity. The amount of Pd leached was determined using ICP analysis (Table 4). In addition, this stability confirms that the release of Pd is controlled by the chelating effect of the porphyrin macrocyclic ligand.

4 | CONCLUSIONS

We have synthesized a palladium organocatalyst as a robust and heterogeneous catalyst in the Suzuki coupling reaction. Easy separation of the catalyst and control of the release of palladium into the reaction mixture because of strong bonding between porphyrin and palladium are factors contributing to this catalyst being reusable. In addition, the experimental results confirm that a broad variety of functional groups can be used in this type of catalytic reaction.

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