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Synthesis and characterization of a new Pd(II)-Schiff base complex [Pd(APD)₂]: An efficient and recyclable catalyst for Heck-Mizoroki and Suzuki-Miyaura reactions

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Graphical Abstract Synopsis:

Synthesis of a new Schiff base ligand and its palladium complex [Pd(APD)₂] have been reported. The ligand and complex are structurally characterized. Complex acts as an efficient catalyst for Heck-Mizoroki and Suzuki-Miyaura coupling reactions with good Turnover number.





Synthesis and Characterization of a new Pd(II)-Schiff base complex [Pd(APD)₂]: An efficient and recyclable catalyst for Heck-Mizoroki and

3 Suzuki-Miyaura reactions

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5

10 Abstract:

The synthesis of a new Schiff base ligand "4-((Z)-((Z)-3-hydroxy-1,3-diphenylallylidene)amino)11 -1,5-dimethyl-2-phenyl-1H-pyrazol-3(2H)-one (APD)" and its palladium complex [Pd(APD)₂] is 12 13 described. The ligand and complex are characterized by FTIR, FESEM, EDX, Elemental analyses and Mass spectrometry. The structure of the ligand is also confirmed by single crystal 14 X-ray determination and ¹H NMR data. The complex is insoluble in almost all common organic 15 solvents. It has been used as an efficient catalyst in a series of Heck-Mizoroki and Suzuki-16 Miyaura coupling reactions giving good TON and TOF. The ease of synthesis, air-stability and 17 18 recyclability are some of the important characteristics of the synthesized catalyst.

19 Keywords: Schiff base, crystal structure, Pd(II) complex, C-C cross coupling reactions

20 1. Introduction:

The C-C bond formation and functional group transformation have emerged as 21 exceedingly important methodologies for the preparation of organic compounds. The catalytic 22 23 emergence of C-C bond formation is one of the most powerful tool for the construction of complex organic molecules [1-2]. Such methodologies have been successfully exploited in the 24 synthesis of a number of natural products, bioactive compounds and materials [3-6]. Among 25 numerous C-C bond formation reactions, Heck, Suzuki, Sonogashira, Tsuji-Trost, Stille, Negishi, 26 and Hiyama-coupling reactions occupy important places [7]. Since the Heck-Mizoroki and 27 Suzuki-Miyaura reactions are frequently used on a large scale for the preparation of 28 pharmaceuticals, agrochemicals, polymers, natural products and advanced materials in chemical 29 industries, we were interested to develop new efficient catalysts for these reactions [8]. 30

In simple words, Heck-Mizoroki and Suzuki-Miyaura may be defined as aryl olefination 31 /vinylation and aryl arylation, respectively [9]. A perusal of the literature reveals that these 32 reactions have been carried out in presence of a large number of phosphine based palladium 33 catalysts [10-11]. The phosphine ligands are toxic, air-sensitive, expensive and difficult to 34 synthesise. In order to circumvent these inherited drawbacks, a quest for the rational design of 35 new catalysts for C-C bond-forming reactions was realized [12]. In this direction, the 36 development of palladium complexes bearing N-heterocyclic carbenes (NHC) or nitrogen-donor 37 ligands is noteworthy [13-14]. Although spectacular success in these reactions was achieved 38 using Pd-NHC complexes, the multistep tedious synthesis of NHC ligands remained a synthetic 39 challenge, and it precluded their large scale industrial application. 40

The ease of synthesis of Schiff base ligands and the thermal/chemical stability of the resultant complexes have resulted in numerous industrial applications [15-16]. Schiff base complexes of palladium(II) have been used extensively as catalysts in a variety of organic reactions [17], such as olefin polymerization [18], hydrogenation of olefins, and removal of toxic metals [19].

The last decade has witnessed the application of Pd(II) Schiff base complexes, containing no phosphine Ligands, in the Heck-Mizoroki and Suzuki-Miyaura reactions [20-23]. Therefore, in continuation of our research interest on the synthesis, structural characterization and catalytic applications of transition metal complexes [24-26], we herein, report a new palladium(II) Schiff base complex as an efficient catalyst in Heck-Mizoroki and Suzuki-Miyaura reactions.

51 **2. Experiment:**

52 2.1. Synthesis of Schiff base ligand "4-((Z)-((Z)-3-hydroxy-1,3-diphenylallylidene)amino)-1,5 53 dimethyl-2-phenyl-1H-pyrazol-3(2H)-one" (APD)

4-Aminoantipyrene (0.204 g, 1 mmol) dissolved in 3 mL ethanol was added drop-wise to an ethanolic solution (3 mL) of 1,3-diphenylpropane 1,3-dione(0.224 g, 1 mmol). The light yellow solution was heated to reflux for 4 hrs and then cooled to room temperature to give yellow crystals. The crystals were filtered, washed with ice-cold ethanol and air-dried at room temperature. Yield: 0.340 g (83%). ¹H NMR (CDCl₃, 25 °C, 400 MHz): δ 11.77 (s, 1H, enolic OH), 7.94-7.96 (s, 2H, Ar *H*), 7.49-7.50 (s, 2H, Ar *H*), 7.40-7.44 (m, 5H, Ar *H*), 7.28-7.33 (m, 3H, Ar *H*), 7.26-7.28 (d, 3H, Ar *H*), 6.10 (s, 1H, -(C₆H₅)C=CH-), 2.87 (s, 3H, NCH₃), 2.01 (s,

- 3H, CCH₃). Selected FTIR (KBr), cm⁻¹: 3151 (ν OH), 1672 (ν C=O), 1558 (ν C=N), 1406 (ν
 C=C). MS (ESI; m/z): Calculated for C₂₆H₂₃N₃O₂409.18, Found 410.14 (M+H)⁺.
- 63 2.2. Synthesis of the complex "bis(((1Z,3Z)-3-((1,5-dimethyl-3-oxo-2-phenyl-2,3-dihydro-1H-
- 64 pyrazol-4-yl)imino)-1,3-diphenylprop-1-en-1-yl)oxy)palladium," [Pd(APD)₂]

Palladium(II) acetate (0.122 g, 0.5 mmol) was added to a suspension of the Schiff base ligand APD (0.410 g, 1 mmol) in methanol (10 mL) at room temperature. The reaction mixture was stirred for 12 h at room temperature to give a light greenish yellow precipitate which was filtered, washed with cold methanol and dried vacuum over anhydrous CaCl₂. Yield: 0.346 g (75%), Selected FTIR (KBr), cm⁻¹: 1672 (v C=O), 1499 (v C=N), 1401 (v C=C), 580 (v Pd-O), 498 (v Pd-N). LC-MS (TOF ES⁺; m/z): Calculated for C₅₂H₄₄N₆O₄Pd 922.25, Found 923.70 (M+H)⁺.

72

73 **3. Results and discussion:**

A new Schiff base ligand (APD) was synthesized in single step by the reaction of 4-74 75 aminoantipyrene with 1,3-diphenylpropane 1,3-dione in refluxing ethanol and isolated in high yield (83%) as yellow crystalline solid. The ligand was fully characterized by FTIR, FESEM, 76 77 EDX, Elemental analyses, Mass and ¹H NMR. The structure of the ligand was also confirmed by single crystal X-ray analysis [27-28] (Fig. 1). A summary of the crystallographic and refinement 78 data of the APD ligand is given in Table 1 and selected bond lengths and bond angles are listed 79 in **Table 1S**. The reaction of the ligand with palladium acetate at room temperature in methanol 80 yielded the complex [Pd(APD)₂] as a greenish yellow solid (Scheme 1). The complex was found 81 82 to be insoluble in almost all organic solvents, however, it was fully characterized by FTIR, FESEM, EDX, Elemental analysis, and TGA-DTG and ESI-Mass spectrum. The single crystals 83 of the complex could not be grown by virtue of its insolubility in most organic solvents. The 84 85 ESI-Mass spectrum of the complex shows a peak at m/z 923.70 corresponding to the [M+H]⁺ cation (Fig. 3S). 86

The FTIR spectrum of the Schiff base ligand exhibited three prominent peaks at 3194 cm⁻¹, 1673 cm⁻¹ and 1558 cm⁻¹, corresponding to v OH, v (C=O) and v (C=N) of azomethine group, respectively (**Fig. 2**). However, the FTIR spectrum of the complex showed peaks at 1672 cm⁻¹ and 1499 cm⁻¹ which were assigned to v (C=O), and v (C=N), respectively. The complete

disappearance of v OH confirmed the deprotonation of the hydroxyl group. A comparison of the 91 FTIR spectra of the complex and the ligand clearly indicated that on complex formation, the 92 v (C=N) stretching frequency was shifted from 1558 cm⁻¹ in free ligand to 1499 c m⁻¹ in the 93 complex (lowering by $\Delta = 59$ cm⁻¹), confirming the coordination of the nitrogen atom of 94 azomethine group of ligand to the metal center [29]. No noticeable change in the C=O stretching 95 frequency of the ligand was observed upon complexation. This confirmed that the C=O group of 96 pyrazole ring of ligand remained intact. The appearance of a new peak in the FTIR of the 97 complex at 580 cm⁻¹ assignable to v Pd-O indicated the coordination of the enolic oxygen to the 98 palladium [30-31]. 99

100 The FESEM micrographs of the APD ligand (**Fig. 3a**) and the complex [Pd(APD)₂] (**Fig** 101 **3b**) displayed blocked shaped smooth and irregular rough surface morphologies, respectively. 102 From the micrographs, it can be concluded that surface roughness had increased on complex 103 formation. The EDX provided the detailed chemical analysis of Schiff base ligand APD (**Fig 3c**) 104 and its palladium complex (**Fig 3d**). The EDX analysis of the complex confirmed the presence of 105 all constituent atoms, i.e. C, N, O and Pd. The palladium content, based upon EDX analysis, was 106 found to be 14.26 % by weight.

107 The TGA of the complex was carried out in the temperature range 40-730 °C with a 20 108 °C/min interval in nitrogen atmosphere to assess the stability and mode of decomposition of the 109 synthesized complex (**Fig. 4S**). Above 175 °C, the TGA/DTA curve exhibits three steps of 110 weight loss. Complex shows a very low weight loss of 2% supported by an exothermic peak at 111 about 230 °C, which may correspond to the loss of or decomposition of one ligand moiety and 112 the framework is quite stable up to 450 °C. In the temperature range 230- 450 °C, a 65% weight 113 loss was observed suggesting the concomitant loss of the second ligand unit from the compound.

115 *Catalytic studies:*

After synthesis and characterization of the [Pd(APD)₂] complex, it was screened for its
catalytic activity in Heck-Mizoroki and Suzuki-Miyaura C-C cross coupling reactions (Scheme
2) [32]. The results obtained in Heck-Mizoroki and Suzuki-Miyaura reactions with Pd-catalyst
are given below.

120

122 Catalyst testing for the Heck-Mizoroki reaction:

A model reaction was performed by stirring 4-methylstyrene with bromobenzene in DMF-H₂O 123 (1:1) using 0.2 mol % of the Pd(II) Schiff base catalysts at 80°C for 4 h. The results of the 124 different reaction conditions such as, variation of temperature, solvent, bases, catalyst loading 125 etc. are summarized in Table 2. A blank reaction (without palladium complex) between 4-126 methystyrene and bromobenzene in DMF-H₂O (1:1) under appropriate conditions (Table 2, entry 127 19) yielded no product. However, the reaction in presence of 0.05 and 0.1 mol % of complex 128 gave 68% and 82% yield of the product (Table 2, entries 10 & 11). The best yield of the product 129 was obtained using 0.2 mol % of the complex (Table 2, entry 4). On the other hand, increasing 130 the catalyst loading from 0.2 mol % to 0.5 mol % did not improve the yield of the product (Table 131 2, entry 12). Therefore, 0.2 mol % of the catalyst was found to be optimal for the coupling 132 reaction (Table 2, entry 4). A reaction between 4-methylstyrene with bromobenzene was carried 133 134 out in presence of Pd(OAc)₂ (0.2 mol %) (without any ligand) to give low yield (Table 2, entry 135 5). However, the same reaction with $Pd(OAc)_2$ and Schiff base ligand (1:2 molar ratio) under the same reaction conditions, resulted in moderate yield of the desired coupling product (Table 2, 136 entry 6). The presence of Schiff base ligand has resulted in enhancement of the yield [14-15]. 137 138 However, the best yield (95 %) was obtained using a pre-formed, isolated complex [Pd(APD)₂] (Table 2, entry 4). After optimization of catalyst loading, solvent, base, temperature and reaction 139 time were optimized. The reaction was also carried out in a number of solvents such as, H₂O, 140 CH₃CN, DMF, CH₃OH etc. and in presence of different bases such as Na₂CO₃, KOH, NaOH and 141 CH₃COONa (Table 2, entries 1-19). The best result was obtained with 0.2 mol % of catalyst, 1 142 143 equiv. of K_2CO_3 at 80°C (Table 2). The DMF-H₂O mixture (1:1) was found to be the best solvent 144 (Table 2, entry 4).

With the optimized reaction conditions in hand, the scope of the Heck reaction was 145 extended to a variety of substituted aryl/hetero-aryl bromides/iodides and substituted olefins. The 146 147 reactions with the aryl bromides required a longer time as compared to aryl iodide. Aryl bromide or iodide with electron-donating methoxy group (Table 3, entries 7, 9, 11 & 13,) or an electron-148 withdrawing group (Table 3, entries 12, 14 & 16), both reacted smoothly under optimized 149 conditions to give the desired products in almost quantitative yields. The reaction with hetero-150 aryl substrate, i.e. 2-bromopyridine with styrene under optimized condition resulted in 75% yield 151 of the desired coupling product (Table 3, entry 15). The reaction of chloro-substrates, instead of 152

bromo- and iodo-substrates, did not succeed under optimized conditions presumably owing to less reactivity of C-Cl bond due to higher bond energy. The isolated products were fully characterized by ¹H and ¹³C NMR. Furthermore, the catalytic activity of the complex [Pd(APD)₂] was compared with previously reported catalysts [10, 33-34] for Heck-Mizoroki coupling reaction in terms of temperature, catalytic loading, time etc (Table 4). Our catalyst gave better yields at low temperature using less amount of catalyst in aqueous medium.

159 Catalyst testing for the Suzuki-Miyaura reaction:

A model reaction between 4-methoxybromobenzene and 4-methylphenylboronic acid 160 was chosen for optimization of catalyst loading, solvent, base and the reaction temperature 161 (Table 5). When the reaction was carried out in the absence of palladium complex in DMF-H₂O 162 (1:1), no coupling product was formed (Table 5, entry 20). When the reaction was carried out 163 with 0.1 mol % catalyst loading, product was isolated in 68% yield (Table 5, entry 2). It was 164 165 observed that the reaction was completed in 4.5 h using 0.2 mol % [Pd(APD)₂] as a catalyst in DMF-H₂O at 80 °C (Table 5, entry 6). No significant improvement in yield of biaryl product was 166 noticed when the catalyst loading was increased from 0.2 mol% to 0.5 mol% under optimized 167 reaction conditions (Table 3, entries 7, 9, 11 & 13,). Therefore, 0.2 mol% catalyst loading was 168 169 found to be optimum. Further the reaction between 4-methoxybromobenzene and 4methylphenylboronic acid carried out in presence of Pd(OAc)₂ alone resulted in low yield (52%) 170 171 of the product (Table 5, entry 7). However, the reaction in presence of Pd(OAc)₂ and Schiff base ligand (1:2 molar ratio) under the optimized conditions resulted in only 64% yield of the desired 172 coupling product (Table 5, entry 8). The best yield of the product was achieved when isolated 173 [Pd(APD)₂] complex was used as the catalyst (Table 3, entries 6). To optimize the suitable 174 solvent, the reaction was performed in the presence of various solvents such as H₂O, CH₃CN, 175 DMF, DMF-H₂O (1:1), CH₃OH, *i*PrOH, CH₃CH₂OH, H₂O/CH₃CH₂OH (1:1) and H₂O/*i*PrOH 176 (1:1) (Table 5). Among all solvents used, the best result was obtained in a 1:1 (by volume) 177 mixture of DMF-H₂O (Table 5, entry 6). A number of bases were used, however, K₂CO₃ was 178 found to be the most efficient base (Table 5, entries 1-20). 179

180 Subsequently, all reactions were carried out under optimized conditions with a 181 structurally diverse range of aryl iodide and aryl/hetero-aryl bromide with arylboronic acid to 182 produce the corresponding biaryls (Table 6). The electron-withdrawing and electron-releasing 183 substituents on both aryl halide and arylboronic acid (Table 6, entries 2-14) afforded the

coupling products in good to excellent yields (87-95%). The substituent in the meta-position 184 (Table 6, entry 10) of phenylboronic acid resulted in lower yields than the para-position (Table 185 6, entry 2) presumably due to the steric hindrance. The reaction with hetero-aryl substrate, i.e. 2-186 bromopyridine with phenylboronic acid under optimized condition resulted in 72% yield of the 187 desired coupling product (Table 6, entry 15). However, reactions with any chloride under similar 188 conditions were unsuccessful. All isolated products were fully characterized by ¹H NMR and ¹³C 189 NMR spectroscopic methods (Supplementary Material). A plausible mechanism for Suzuki 190 coupling reaction, based on previous reports [35], is suggested in Scheme 3. 191

192 *Recyclability test:*

The heterogeneous nature of the catalyst facilitated its easy removal by simple filtration under 193 gravity. After filtration, the catalyst was washed with water and methanol and dried under 194 vacuum. The recyclability of [Pd(APD)₂] complex was tested in both Heck-Mizoroki and 195 196 Suzuki-Miyaura coupling reactions. The complex could be recycled up to three times (Fig. 5S), 197 however, a progressive decrease in yields of product was observed. The decrease in yield of products may be due to the physical loss of the catalyst during separation, filtration and washings 198 among each run. The decrease in yields may also be due to the passivation of catalyst surface 199 200 after three cycles.

201

202 **4. Conclusion:**

In conclusion, a new Schiff base ligand (**APD**) was synthesized for the first time and characterized by single crystal structure determination. The reaction of ligand with palladium acetate in methanol afforded the corresponding palladium complex [Pd(APD)₂] which was characterized by various physico-chemical methods. The heterogeneous nature and the catalytic activity of the complex has been explored in Heck-Mizoroki and Suzuki-Miyaura coupling at a low (0.2 mol %) catalyst loading. The present methodology offers good turnover numbers (TON) in both Heck-Mizoroki and Suzuki-Miyaura cross coupling reactions.

210

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215		
216	Suppl	ementary data
217		Supplementary data related to this article.
218	Refere	ences:
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267	[27]	Crystal data for APD ligand were obtained at 295 K with a Bruker Kappa diffractometer
268		equipped with a CCD detector, employing Mo Ka radiation ($\lambda=0.71073$ Å), with the
269		SMART suite of programs using a Bruker Kappa Apex Four Circle CCD diffractometer,
270		C ₂₆ H ₂₃ N ₃ O ₂ , monoclinic, space group P21/n, a=8.6261(3) Å, b=18.5933(6) Å,
271		c=13.4820(4), V = 2161.94(12) Å3, Z = 4, Dx = 1.258 g/cm3, $F(000) = 864$. A total of
272		6643 reflections were collected and the structure was refined by full-matrix least-squares
273		on F^2 . The final refinement [I > 2ns (I)] gave $R_1 = 0.0480$, w $R_2 = 0.1328$.
274	[28]	Crystallographic data for APD ligand has been deposited at the Cambridge
275		Crystallographic Data Centre as supplementary publication number CCDC 1441973.

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- This data can be obtained free of charge from the Cambridge Crystallographic Data
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- General procedure for the Suzuki-Miyaura reaction: A mixture of aryl halide (1 mmol), 294 arylboronic acid (1 mmol), K₂CO₃ (1 mmol), and the Pd- Schiff base complex (2.1 mg, 295 0.2 mol %) in DMF-H₂O (1:1) was stirred at 80°C for 3-5 h. The progress of reaction was 296 monitored by TLC until the complete consumption of the aryl halide. After the reaction, 297 the mixture was cooled down to room temperature and repeatedly extracted with ethyl 298 acetate. The combined organic layer was separated, dried over Na₂SO₄ and evaporated 299 under reduced pressure. The residue was purified by column chromatography on silica 300 gel to give the corresponding coupling products in up to 95% isolated yield. The products 301 were confirmed by ¹H and ¹³C NMR. 302
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309	
310	List of Scheme's caption
311	Scheme 1. Synthesis of Schiff base ligand (APD) and [Pd(APD) ₂] complex
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- 339 Miyaura (2b) coupling reactions





Scheme 3. Plausible mechanism for the Suzuki-Miyaura coupling reaction





Fig. 1. ORTEP diagram of APD ligand with 50% ellipsoid probability







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Fig. 2. FT-IR Spectra of APD ligand and [Pd(APD)₂] complex



Fig. 3. FESEM micrographs of (a) APD ligand, (b) [Pd(APD)₂] complex and EDX Analysis of
 (c)APD ligand, (d) [Pd(APD)₂] complex

Table 1: Crystallographic and refinement data for APD ligand

CCDC No.	1441973	Space group	P 21/n
Chemical formula	C ₂₆ H ₂ N ₃ O ₂	Volume	2263.8(4) Å ³
Formula weight	409.47 g/mol	Z	4
Temperature	295 K	Density (calculated)	1.496 g/cm^3
Wavelength	0.71073 Å	Absorption coefficient	1.002 mm^{-1}
Density (gm cm ⁻³)	1.258	R int	0.0567
Volume	2161.94 (12)	$R_1[I>2\delta(I)]$	0.0513
Crystal habit	yellow block	wR_2 (all data)	0.1145
Crystal system	Monoclinic		
Unit cell dimensions	a = 8.6261(3) Å b = 18.5933(6) Å c = 13.4820(4) Å $a = 90^{\circ}$ $\beta = 91.111(2)^{\circ}$ $\gamma = 90^{\circ}$		

Entry	Catalyst	Solvents	Base	Temp	Time	Yie
·	loading			(°C)	(h)	(%
1	0.5	DMF	KaCOa	80	7	7
2	0.2	DMF	K_2CO_3	80	8	7
3	0.2	DMF-H ₂ O	K_2CO_3 K_2CO_3	80	7	9
4	0.2	DMF-H ₂ O		80	4	9
5	0.2#	DMF-H ₂ O	K_2CO_3	80	4	6
6	0.2##	DMF-H ₂ O	K_2CO_3	80	4	7
7	0.2	CH ₃ CN	K ₂ CO ₃	80	8	6
8	0.2	DMF-H ₂ O	Na ₂ CO ₃	80	6	8
9	0.2	DMF-H ₂ O	K ₂ CO ₃	100	4	9
10	0.05	DMF-H ₂ O	K ₂ CO ₃	80	4	6
11	0.1	DMF-H ₂ O	K ₂ CO ₃	80	4	8
12	0.5	DMF-H ₂ O	K ₂ CO ₃	80	4	8
13	0.2	H ₂ O	K ₂ CO ₃	100	12	5
14	0.2	DMF-H ₂ O	K_2CO_3	RT	12	6
15	0.2	MeOH	K ₂ CO ₃	60	12	tra
16	0.2	DMF-H ₂ O	KOH	80	7	6
17	0.2	DMF-H ₂ O	NaOH	80	7	6
18	0.2	DMF-H ₂ O	CH ₃ COONa	80	4	7
19	-	DMF-H ₂ O	K ₂ CO ₃	80	7	-
Base (**Yiel [#] Only I ^{##} Pd(O	(0.75 mmo d after colu Pd(OAc) ₂ us Ac) ₂ /Schiff	l, 1.5 equiv). umn chromate ed as catalyst base ligand (1	ography :2 ratio) as catalys	st		
) 7						

Table 2. Optimization of the Heck-Mizoroki reaction conditions *

371	Table 3. Heck-Mizoroki reactions wi	th different substituents	catalyzed by $[Pd(APD)_2]$ complex

372 under optimized reaction conditions

		RI	x + 🔌	$R_2 \qquad \frac{[Pd(APD)]}{DMF; H_2O}$	0 ₂] (0.2) mol%) → (1:1), 80°C, 3-4h • CO ₃	R ₁	▶ ^R 2	
		X=Br, I, Z≠ R ₁ = H, CH COCH ₃ , O	=CH, N R ₂ = Pl I ₃ , CHO, 4-CH ₃ l CH ₃	h, 4-(CH ₂ Cl)Ph, Ph, COOCH ₃				
Entry	Х	Ζ	R_1	R ₂	Time (h)	Yields (%)	TON	TOF (h ⁻¹)
1	Br	СН	Н	C ₆ H ₅	4.0	92	475	119
2	Br	СН	Н	CH ₃ -C ₆ H ₄	4.0	95	514	129
3	Br	СН	СНО	CH ₃ -C ₆ H ₄	3.5	91	492	141
4	Br	СН	COCH ₃	C_6H_5	4.0	90	464	116
5	Ι	СН	OCH ₃	C ₆ H ₅	4.0	94	485	162
6	Ι	СН	Н	CH ₃ -C ₆ H ₄	3.5	93	480	137
7	Br	СН	OCH ₃	COOCH ₃	3.5	89	482	138
8	Ι	СН	Н	ClCH ₂ -C ₆ H ₄	3.5	85	461	132
9	Ι	СН	OCH ₃	CH ₃ -C ₆ H ₄	3.0	98	530	177
10	Br	СН	СНО	COOCH ₃	3.5	92	475	135
11	Br	СН	COCH ₃	COOCH ₃	3.5	93	504	144
12	Br	СН	СНО	CH ₃ -C ₆ H ₄	3.5	92	498	138
13	Br	СН	OCH ₃	CH ₃ -C ₆ H ₄	3.5	95	514	147
14	Ι	СН	СНО	COOCH ₃	3.5	92	499	143
15	Br	N	Н	C_6H_5	4	75	346	86

³⁷³

Table 4. A comparison study of [Pd(APD)₂] complex with the previous reported catalysts in

375 Heck-Mizoroki reactions in terms of temperature, catalyst loading, time.

Entry	Catalyst	Catalyst	Temperature	Time	Yields	Reference
		loading			(%)	

1	Pd(II) bis thiosemi	0.1 mol %	100°C	8h	60-98	10
	carbazone					
	complex					
2	Pd(II)- salen	0.5 mol %	130°C	6h	20-97	33
	complex					
3	Pd-Imidazolium	2.0 mol %	$25^{\circ}C$	3-5h	32-91	34
	Carbene					
	complex					
4	$[Pd(APD)_2]$	0.2 mol %	$80^{\circ}C$	3-4h	85-98	This work
	complex					7

Table 5. Optimization of the Suzuki-Miyaura reaction conditions *

Br Br H H H H H H H H H H H H H H H H H	[Pd(APD) ₂] Solvent, Base, Temperature
осн _з сн _з	

Entry	Catalyst	Solvents	Base	Temp	Time	Yield**
	loading			$(^{\circ}C)$	(h)	$(\%)^{b}$
	(mol %)					
1	0.2	DMF	K ₂ CO ₃	80	5	67
2	0.1	DMF	K_2CO_3	80	5	68
3	0.2	DMF-H ₂ O	K_2CO_3	80	7	90
4	0.2	DMF-H ₂ O	K_2CO_3	80	3	79
5	0.2	CH ₃ CN	K_2CO_3	110	5	70
6	0.2	DMF-H ₂ O	K ₂ CO ₃	80	4.5	94
7	$0.2^{\#}$	DMF-H ₂ O	K_2CO_3	80	4.5	52
8	$0.2^{\#\#}$	DMF-H ₂ O	K_2CO_3	80	4.5	64
9	0.2	DMF-H ₂ O	K_2CO_3	100	4.5	90
10	0.5	DMF-H ₂ O	K_2CO_3	80	4.5	90
11	0.2	DMF-H ₂ O	Na ₂ CO ₃	80	5	81
12	0.2	H_2O	K_2CO_3	100	12	45
13	0.2	<i>i</i> PrOH	K_2CO_3	80	4.5	55
14	0.2	<i>i</i> PrOH-H ₂ O	K_2CO_3	80	4.5	62
15	0.2	CH ₃ CH ₂ OH	K_2CO_3	80	4.5	48
16	0.2	CH ₃ CH ₂ OH-H ₂ O	K_2CO_3	80	4.5	50
17	0.2	DMF-H ₂ O	K_2CO_3	RT	18	60
18	0.2	DMF-H ₂ O	KOH	80	7	65
19	0.2	DMF-H ₂ O	NaOH	80	7	68
20	-	DMF-H ₂ O	K_2CO_3	80-100	24	-

*Reaction conditions: Aryl halide (0.5 mmol, 1.0 equiv), Phenyl boronic acid (0.6 mmol, 1.2 equiv),

Base (0.75 mmol, 1.5 equiv). **Yield after column chromatography.

385	[#] Only Pd(OAc) ₂ used as catalyst
386	^{##} Pd(OAc) ₂ /Schiff base ligand (1:2 ratio) as catalyst

387

Table 6. Suzuki-Miyaura reactions with different substituents catalyzed by [Pd(APD)₂] complex

389 under optimized reaction conditions.

	R		HO) ₂ B	$R_3 = \frac{[Pd(APD)_2]}{DMF: H_2O}$	(1:1), 80°C, 3-5h	RI		
X=Br, I; Z=CH, N R_1 = H, CH ₃ , CHO, R_3 = CH ₃ , OCH ₃ , Cl, Br, F, napthyl COCH ₃ , OCH ₃								
Entry	Х	Z	R ₁	R ₃	Time (h)	Yields	TON	TOF (h ⁻¹)
1	Br	СН	Н	Н	4.5	91	470	105
2	Br	СН	Н	4-CH ₃	4.0	92	475	118
3	Br	СН	OCH ₃	4-CH ₃	4.0	95	514	129
4	Br	СН	COCH ₃	Н	4.0	93	480	120
5	Br	СН	OCH ₃	4-OCH ₃	4.0	92	477	119
6	Ι	СН	OCH ₃	4-CH ₃	3.5	94	509	145
7	Br	СН	Н	4-CH ₂ CH ₃	4.0	90	464	116
8	Br	СН	Н	4-OCH ₃	4.0	92	475	119
9	Br	СН	OCH ₃	4-CH ₂ CH ₃	4.5	93	504	112
10	Br	СН	Н	3-CH ₃	4.5	90	464	103
11	Br	СН	Н	4-Cl	4.5	89	459	102
12	Br	СН	OCH ₃	4-Cl	4.5	90	464	103
13	Br	СН	Н	3-CN	4.5	88	476	106
14	Br	СН	OCH ₃	4-F	4.5	87	471	105
15	Br	Ν	Н	Н	4.5	72	332	74

Highlights:

- Synthesis of a new Schiff base ligand and its palladium complex [Pd(APD)₂]
- Ligand structure determined by single crystal X-ray study
- Complex is a good catalyst for Heck-Mizoroki and Suzuki-Miyaura coupling reactions
- Catalyst recyclability up to three times