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ARTICLE

Highly active recyclable heterogeneous Pd/ZnO nanoparticles catalyst: Sustainable developments for the C-O and C-N bond cross-coupling reactions of aryl halides under ligand-free condition

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An efficient Pd supported on ZnO nanoparticles for the ligand-free *O*-arylation and *N*-arylation of phenols and various N-H heterocycles with aryl chlorides, bromides, and iodides were readily synthesized and characterized. The amount of palladium on ZnO is 9.84 wt% (0.005 g of the catalyst contains 462×10^{-8} mol% of Pd) which was determined by ICP analysis. This nano sized Pd/ZnO with an average particle size of 20-25 nm and specific surface area 40.61 m²/g was used as a new reusable heterogeneous catalyst for the formation of C-O and C-N bonds in organic synthesis. This protocol gives arylated product in satisfactory yields without any N₂ or Ar flow. The catalyst can be recovered and recycled several times without marked loss of activity.

Introduction

Transition metal-catalyzed carbon–oxygen and carbon–nitrogen bonds formation with aryl halides and aromatic phenols and amines is a powerful tool to prepare *O*- and *N*-containing compounds which have high applicability's in synthetic, biological, pharmaceutical, and materials science.¹ Therefore, intensive efforts have been devoted to developing more efficient and practical routes to prepare the carbon-heteroatom coupling reactions starting from simple precursors. Under the classical conditions, the Ullmann reaction^{2,3} is still straight forward protocol to form the carbon-heteroatom bonds, but, have limitations because of the harsh reaction conditions such as high temperatures, requirement of stoichiometric amounts of copper reagents, long reaction times, and low yields.^{2c}

Various reactions have been reported for the synthesis of aryl ethers and *N*-arylated compounds by employing intermolecular reaction between aryl halide and phenol or amine using catalytic protocols.⁴ However, the synthesis of aryl ethers from aryl fluorides or chlorides that are activated by strong electron withdrawing groups, located in the *ortho*, *para*, or *meta* positions requirement of the presence of these withdrawing groups, that is a sever limitation on the variety of aryl ethers available through nucleophilic aromatic substitution reaction. For these limitations, only limited papers have contributed to *O*-arylation of phenols with aryl bromides or chlorides as functional substrates or hindered substrates⁵ without the recovery of the catalyst. Many transition metals such as copper and palladium catalyzed C–O,⁶ C–N,^{4a,4d} C–S,⁷ and C–C⁸ bond formation reactions. These catalysts have been carried out with or without ligand to form a resurgence of interest in carbon–heteroatom coupling reactions.⁹

Various readily accessible ligands have been used to carry out Ullmann reaction, such as *N*, *N*- and *N*, *O*-bidentate compounds, phosphazene, ethylene glycol, neocuproine, *N*-methyl glycine, oxime-phosphine oxide ligand, tripod ligand, benzotriazole, 1,2-diaminocyclohexane, β-ketoester, and L-proline.^{9d,10} On the other hand, despite its remarkable usefulness, the Cu-catalyzed Ullmann type reactions, limited by the insolubility of copper salts in organic solvents, harsh reaction conditions (200 °C), long reaction times, high copper loading for aryl bromide and chloride, and sensitivity of the substituted aryl halides to the harsh reaction conditions, making these conditions environmentally unfriendly. For these problems, in recent years some protocols of metal-free *O*-arylation have been reported.¹¹

Chang *et al.*¹² reported Rh catalyzed *O*-arylation of aryl bromides with *N*-heterocyclic carbene (NHC) as ligand and silver salt in toluene at 100 °C for 24 h. Recently, Iranpoor *et al.*¹³ used PdCl₂ supported on silica diphenylphosphinite based ligand for C-O and C-S arylation of aryl halides, but this method was laborious (using PdCl₂ as high cost palladium source, using N₂ flow for preparation of SDPP ligand, using NaOH as strong base and using 2.0 mL 20% aqueous ^tBu₄NOH as solvent). Yang and Xu *et al.*¹⁴ also used copper ferrite (CuFe₂O₄) nanoparticles, for Ullmann C-O coupling reaction. This catalyst system showed some advantages such as low cost and easily recycling by using an external magnet, but this method was also laborious (using 10 mol% of 2,2,6,6-tetramethyl-3,5-heptanedione as ligand, using argon flow, using Cs₂CO₃ as expensive base and using NMP as organic solvent at 135 °C for 24 h).

Recently, nano metal oxides have been prepared and widely used in organic synthesis and industry, because of high surface area of these classes of catalysts. Agawane and Nagarkar^{4d} used 2.5 mol% of nano cerium oxide (ceria, CeO₂) as a heterogeneous catalyst for Ullmann type coupling reactions in DMSO as solvent at 110 °C in air. This catalyst was shown some advantages, for example CeO₂ is a cheaper catalyst compared to related copper and palladium based catalysts, but in this method 1.2 mmol KOH as a strong base was used. Also, Cu₂O metal oxide as recyclable catalyst reported for cross-coupling reaction of aryl halides and phenols in the presence of Cs₂CO₃ as the base in THF at 150 °C.^{6b}

Homogeneous palladium catalysts suffer from a number of drawbacks such as availability, stability, cost of the palladium complexes and phosphine ligands, and not used in industrial application because of the difficult separation and recycling.¹⁵ From these, heterogeneous palladium catalysts have been made and seems particularly well suited since the palladium metal immobilized on to a support (including organic, polymers, or inorganic supports) could be easily removed by filtration leaving products virtually free of palladium residues.¹⁶ Palladium nanoparticles, and colloidal palladium species, have also reported as recycling catalysts.^{17,18} However, these heterogeneous palladium catalysts often suffer from problems such as low catalytic efficiency degradation, the leaching of the metal species, and difficult synthetic procedures.

To the best of our knowledge, there are no studies on C-O, or C-N coupling reactions with ZnO modified with palladium. Therefore, in this paper, was shown Pd/ZnO nanoparticles, to be one of the best highly active and selective catalyst toward bromide over chloride or fluoride in multiple halogenated phenols and various N-H heterocycles. The goal of this work describes in this paper is the synthesis of Pd/ZnO nanoparticles by co-precipitation method with palladium supported on ZnO (the amount of palladium is 462×10⁻⁸ mol% which was determined by ICP) for ligand-free selective arylation of various phenols without any N₂ or Ar flow under air atmosphere.

Results and discussion

Characterization of the catalyst

As part of our interest on the preparation and investigation of the catalytic activity of nano metal oxides,^{19,20} we recently reported the efficiency of Pd/ZnO nanoparticles in the Sonogashira and Mizoroki-Heck reactions.²¹ This catalyst was synthesized and fully characterized by powder X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), thermo gravimetric analyzer (TGA), BET surface area measurement, FT-IR spectroscopy, ICP, and AAS analyzers and some of these results are shown in Table 1.²¹

The SEM and TEM images of the synthesized Pd/ZnO nanoparticles are shown in Figure 1. It should be noted that, due to various reasons such as the same morphology and size distribution of each ZnO and Pd nanoparticles, partially the same contrast of the electron beam through the ZnO and Pd nanoparticles during the TEM analysis and finally owing to the phenomenon such as relative coagulation of the synthesized

nanoparticles, no significant difference was observed between the morphology and structure of ZnO and Pd nanoparticles during characterization by TEM (Figure 1), even after enhancing the contrast by Au sputtering. In addition, calculating the size particles of Pd by XRD was impossible because of very small amounts of Pd loaded on ZnO so the peak of Pd(0) is not strong.

From XPS spectra of 9.8 wt% palladium modified ZnO, it could be seen that the binding energy (BE) of the Pd_{3d5/2} XPS peak was at about 335.5 eV. Thus, the binding energy of Pd_{3d5/2} appeared at 335.5 eV, indicating that Pd exists mainly as the form of zero-valence Pd on ZnO surface (Figur 2). ZnO is a non-stoichiometric compound. Zn impurities in ZnO, behave as *n*-type dopant. Electrons given by the impurities are weakly bound to the Zn⁺ atoms²² and these are the reason for reduction of Pd(II) species to metallic Pd(0) on the catalyst during the preparation. A growth mechanism for reduction of Pd(II) species to metallic Pd(0) in the presence of ZnO for preparation of nano pd/ZnO reported previously.²³

For determination the amounts of Pd supported on ZnO nanoparticles, ICP technique was employed. According to this analysis, the amount of Pd in 0.003 g and 0.005 g of the catalyst was determined as 277×10⁻⁸ and 462×10⁻⁸ mol%, respectively.

Table 1. Characterization data for Pd/ZnO nanoparticles

XRD	Crystallite sizes of ZnO and Pd/ZnO _x were 21-23 nm
BET surface area	40.61 m ² /g
Pore size distribution	1.81 nm
TEM	25 nm
XPS	binding energy (BE) of the Pd _{3d5/2} was 335.5 eV
TGA	percentage of accessible Pd in catalyst, was 2.72±0.01%
ICP	9.84% (w/w)
AAS	9.80% (w/w)

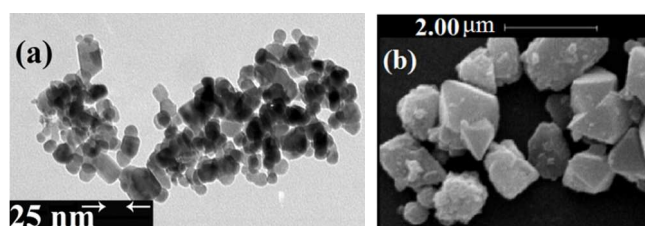


Figure 1. a) TEM and b) SEM images of Pd/ZnO nanoparticles.

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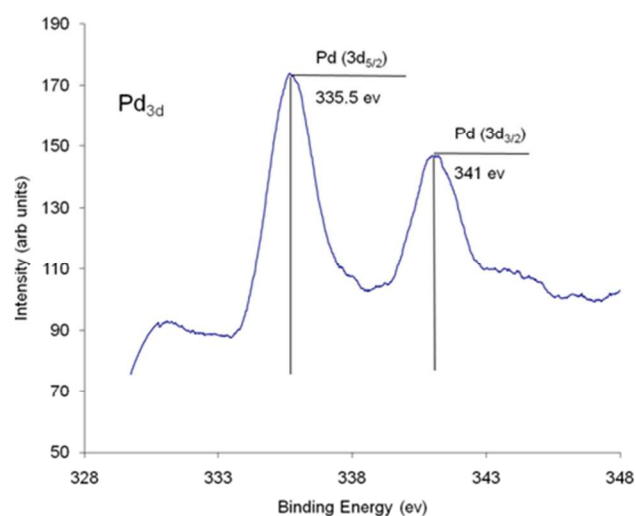
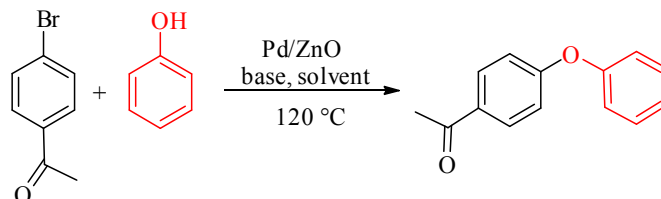


Figure 2. XPS spectra of Pd_{3d} in 9.8 wt%, Pd/ZnO nanoparticles.

Catalytic application of Pd/ZnO nanoparticles: *O*-arylation reaction

In order to discover the optimal reaction conditions, the cross coupling of 1-(4-bromophenyl)ethanone (1 mmol) in the presence of Pd/ZnO nanoparticles was studied in various parameters such as the effect of different solvents, bases and amount of catalyst. The experimental results are summarized in Scheme 1, and Tables 2- 4.



Scheme 1. *O*-arylation of 1-(4-bromophenyl)ethanone and phenol by Pd/ZnO nanoparticles catalyst.

First we optimized the amounts of Pd/ZnO nanoparticles for the reaction between 1-(4-bromophenyl)ethanone and phenol (Table 2). As it can be seen from entries 1-3, with increasing the amount of catalyst from 0.0005 g, the yield of desired product further increases, and reduced the reaction time. Between 0.005 g (entry 3) and 0.009 g (entry 4) of the catalyst, was chosen 0.005 g of the Pd/ZnO nanoparticles (which contains 462×10^{-8} mol% of Pd), because of lower amount of palladium loading. In addition as expected, no reaction occurred with nano ZnO (Table 2, entry 5). According to Table 3, various bases were tested and K₂CO₃ was shown the best result and the corresponding coupling product was obtained in 93% yield (Table 3, entry 1). So, 1 mmol of K₂CO₃ as an inexpensive and readily available inorganic base was used in this study. Results show that Pd/ZnO nanocatalyst, is very efficient and suitable catalyst for the coupling reaction of 1-(4-bromophenyl)ethanone and phenol in solvent free condition (Table 4, entry 6). We then tried this reaction in other solvents. The use of protic polar solvents, such as EtOH and ethane-1,2-diol, which are commonly used in Pd catalyzed coupling reactions, were not effective in the present coupling reaction (Table 4, entries 2, 3).

Table 2. Optimization of the amount of Pd/ZnO nanoparticles in the *O*-arylation reaction^a

Entry	1	2	3	4	5 ^c
Pd/ZnO (g, mol% of Pd ^b)	0.0005, 462×10^{-9}	0.001, 925×10^{-9}	0.005, 462×10^{-8}	0.009, 832×10^{-8}	0.005 g nano ZnO ^c
Time (h)	10	8	5	4	24 ^c
Yield (%) ^d	80	85	93	93	0 ^c

^a Reaction conditions: 1-(4-bromophenyl)ethanone (1 mmol), phenol (1 mmol), Pd/ZnO nanoparticles, and K₂CO₃ (1 mmol) at 120 °C. ^b Determined by ICP. ^c 0.005 g of nano ZnO were used as catalyst. ^d Isolated yield.

Table 3. The effect of base in the *O*-arylation reaction^a

Entry	Base	mmol	Time (h)	Yield (%) ^b
1	K ₂ CO ₃	1	5	93
2	Na ₂ CO ₃	1	7	93
3	KF.2H ₂ O	1	7	93
4	K ₃ PO ₄	1	5	93
5	KOH	1	5	93
6	K ₂ CO ₃	0.5	12	85
7	Cs ₂ CO ₃	1	7	93
8	NaOAc	1	7	85

^a Reaction conditions: 1-(4-bromophenyl)ethanone (1 mmol), phenol (1 mmol), Pd/ZnO nanoparticles (0.005 g), and base (1 mmol) at 120 °C. ^b Isolated yield.

Table 4. The effect of solvents in the *O*-arylation reaction^a

Entry	Solvent	Time (h)	Yield (%) ^c
1 ^b	H ₂ O	5	-
2 ^b	EtOH	6	-
3	Ethane-1,2-diol	9	75
4	DMSO	7	93
5	DMF	6	93
6	Solvent free	5	93
7 ^b	Toluene	15	10

^a Reaction conditions: 1-(4-bromophenyl)ethanone (1 mmol), phenol (1 mmol), Pd/ZnO nanoparticles (0.005 g), K₂CO₃ (1 mmol), and solvent (1 mL) at 120 °C. ^b Reaction conducted at 100 °C. ^c Isolated yield.

After optimized reaction conditions, the coupling reactions between a range of aryl halides (I, Br, and Cl) and phenols were carried out in the presence of Pd/ZnO nanoparticles (0.005 g),

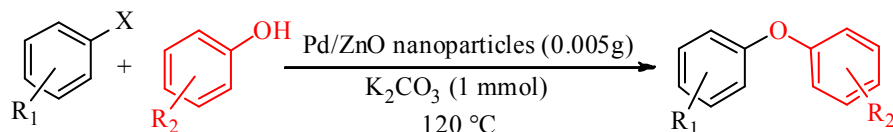
and K_2CO_3 (1 mmol) at 120 °C. As shown in Table 5, aryl iodides with a variety of electron-rich and electron-poor substituent proceeded smoothly, giving the coupling products in good to excellent yields. The reactivity of aryl bromides and chlorides with electron-withdrawing substituent (Table 5, entries 20-27) were higher than those with electron donating substituent (Table 5, entries 15, 16). Also phenols with electron donating substituent such as methoxy and ethyl groups at the *para*, *ortho*, and *meta* position (Table 5, entries 6-8) were reactive than with electron-withdrawing substitute (Table 5, entries 4, 5, and 9). Furthermore, steric hindrance due to the *ortho* substituents on the phenol did not affect the reaction progress (Table 5, entries 7, 10). It is noteworthy that the reaction was chemoselective, for example, reaction between 1-bromo-4-chlorobenzene and phenol gave 4-chlorodiphenylether as only product (Table 5, entry 27).

The recovery and reusability of Pd/ZnO nanoparticles catalyst was also investigated in reaction of 1-(4-bromophenyl)ethanone

with phenol as model reaction (Table 6). After the completion of reaction, Pd/ZnO nanoparticles was recovered by centrifugation and washed with water followed by ethylacetate and then dried in an oven at 80 °C. A new reaction was then performed with reactants under similar conditions. As can be seen in Table 6, Pd/ZnO nanoparticles catalyst could be used more than 5 times without significant changes in activity.

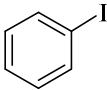
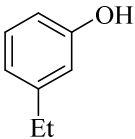
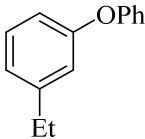
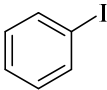
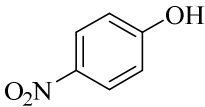
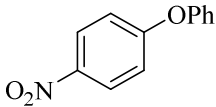
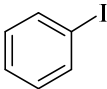
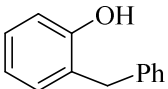
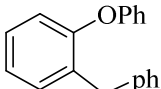
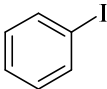
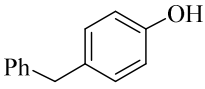
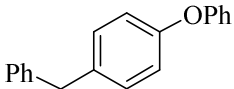
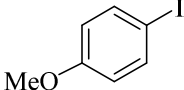
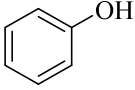
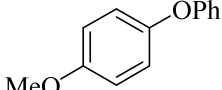
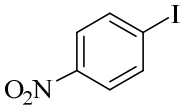
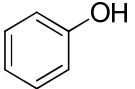
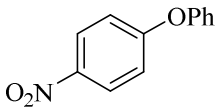
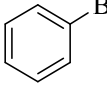
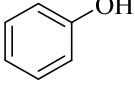
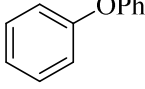
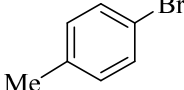
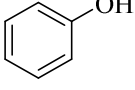
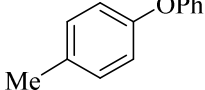
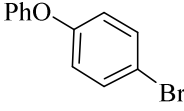
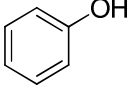
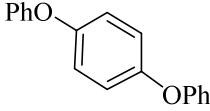
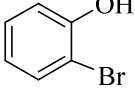
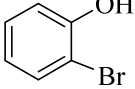
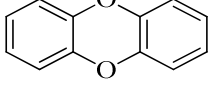
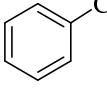
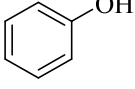
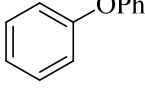
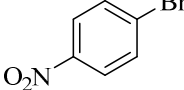
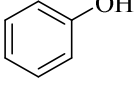
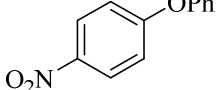
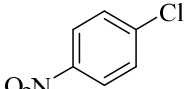
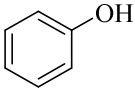
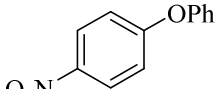
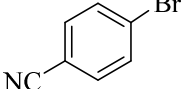
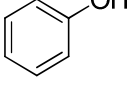
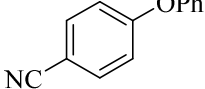
The average amount of palladium leaching in the Pd/ZnO nanoparticles after 5th repeated recycling runs for *O*-arylation reaction was determined by ICP analysis and AAS to be only 0.02 %wt (the initial 9.84 wt% Pd goes to 9.82 wt%). However, the leaching of the catalyst was only 0.02% but this small amount of leaching could be affected in the time of reaction in each reuse recycle. It may be because of the initial loading of Pd on ZnO was also too low. The absence of any obvious decrease leached metal in the filtrate suggests that high stability of the heterogeneous catalyst and confirming that the catalytic process occurs on solid surface.²¹

Table 5. *O*-arylation reaction of aryl halides with phenols^a



Entry	Aryl halide	Phenol	Product	Time (h)	Yield (%) ^b
1				5	98
2				5	95
3				4	95
4				6	90
5				7	90
6				3	98
7				4	95

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8				4	96
9				5	90
10				5	90
11				4	95
12				5	95
13 ^c				4	98
14				15	80
15				20	88
16				15	89
17				12	90
18				20	70
19 ^c				5	90
20 ^c				10	90
21				6	90

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22	12	90
23	5	92
24	10	90
25	11	92
26	5	93
27	6	90

^a Reaction conditions: arylhalides (1 mmol), phenols (1 mmol), Pd/ZnO nanoparticles (0.005 g), and K₂CO₃ (1 mmol) at 120 °C. ^b Isolated yield. ^c Reaction conducted in DMF (1mL).

Also, the XRD pattern of the catalyst before and after fifth recovery is shown in Figure 3, and no changes or impurities were observed.

Table 6. Pd/ZnO nanoparticles catalyzed *O*-arylation reaction^a

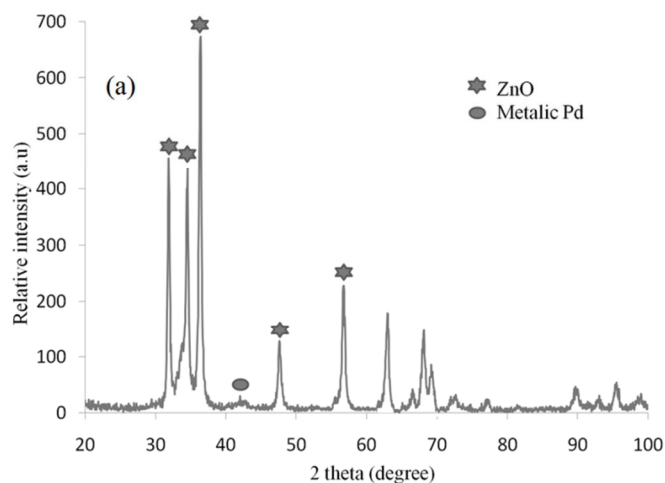
Run	Time (h)	Yield (%) ^b
First	5	93
Second	6	93
Third	7	92
Fourth	8	91
Fifth	9	90

^a Reaction conditions: 1-(4-bromophenyl)ethanone (1 mmol), phenol (1 mmol), Pd/ZnO nanoparticles (0.005 g), and K₂CO₃ (1 mmol) at 120 °C. ^b Isolated yield.

N-arylation reaction

The synthesis of various *N*-arylated hetero aromatic compounds specific *N*-arylimidazoles and *N*-arylbenzimidazoles has attracted significant interest because of the frequent occurrence of these structural units in biologically active inhibitors. In an effort to evolve a better catalytic system, various amounts of Pd/ZnO nanoparticles catalyst were screened for *N*-arylation of benzimidazole and iodobenzene in various parameters such as the effect of different solvents and bases (Table 7). When the reaction was performed with 0.003 g Pd/ZnO nanoparticles (which contains 277×10⁻⁸ mol% of pd determined by ICP) in the presence of K₂CO₃ (1 mmol) as a base, DMF (1 mL), at 120 °C for 10 h, the expected cross-coupling product of 1-phenyl-1H-benzo[d]imidazole was afforded in 95% yield (Table 7, entry 3).

For further optimization of the reaction conditions, the decreasing yields of the coupling product were observed by decreasing the amounts of Pd/ZnO nanoparticles catalyst (Table 7, entries 1-4). The desired reaction was not observed in the absence of Pd/ZnO nanoparticles as catalyst (Table 7, entry 5). To evaluate the effect of the solvent (Table 7, entries 3, 6-11), results showed that solvent free condition is the best choice. For comparison on the efficiency of base in this reaction (Table 7, entries 3, 12-14) K₂CO₃ was found to be the most effective and so, 1 mmol of K₂CO₃ as an inexpensive and readily available inorganic base was used in this study.



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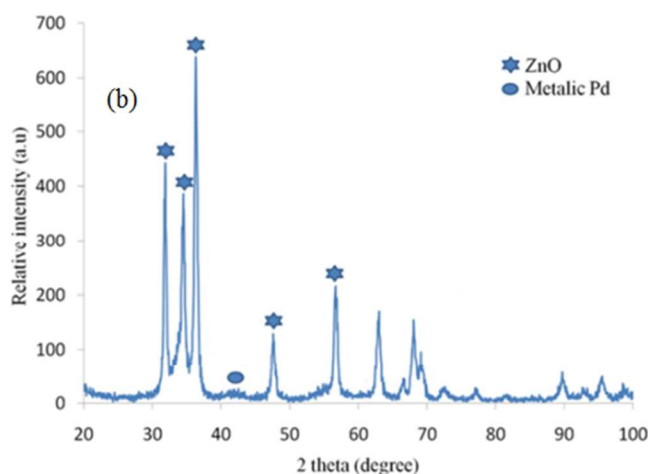
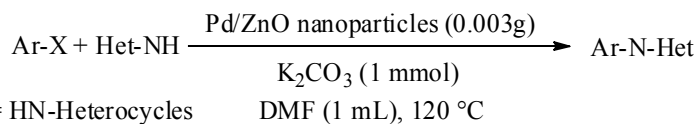


Figure 3. XRD pattern of the Pd/ZnO nanoparticles: a) before and b) after the 5th run recycling in the *O*-arylation reaction.

On the basis of the optimized reaction conditions, the coupling reactions between a range of arylhalides (I, Br, and Cl) and N-H heterocycles were examined (Table 8). Similar to *O*-arylation reactions, it has been found that, aryl iodides with a variety of electron-rich and electron-poor substituent proceeded, giving the coupling products in good to excellent yields (Table 8, entries 1-15). The reactivity of aryl bromides and chlorides with electron-withdrawing substitute (Table 8, entries 16-31) was higher than those with electron donating substituent (Table 8, entries 32-33). We were able to exploit the intrinsic reactivity differences of aryl halides in Pd/ZnO-catalyzed *N*-arylation reactions to couple aryl iodides selectively in the presence of substrates containing fluorides (entry 13). The reaction was also chemo-selective (entries 16-19), for example, reaction between 1-bromo-4-fluorobenzene and pyrrole gave 1-(4-fluorophenyl)-1*H*-pyrrole as only product (entry 16). It is interesting to note that with a free amino group presented in the substrate, the reaction yield was also high and no by-products were observed

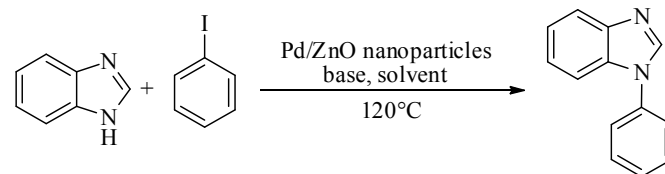
Table 8. Pd/ZnO-catalyzed *N*-arylation of heterocycles with aryl halides



Entry	Ar	X	Het-NH	Product	Time (h)	Yield (%) ^a
1	C ₆ H ₅	I			4	92
2	C ₆ H ₅	I			7	95
3	C ₆ H ₅	I			5	94

(Table 8, entry 10). In addition, *N*-arylation reaction under the same conditions was not observed with primary amino groups on the aromatic rings of aniline even with electron-donating and withdrawing substituents.

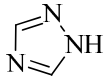
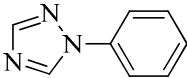
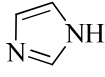
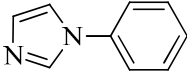
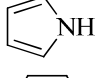
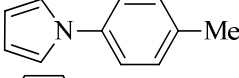
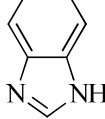
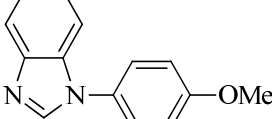
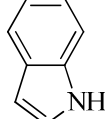
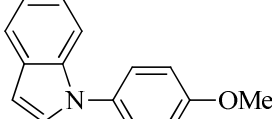
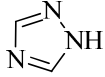
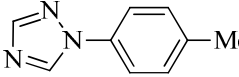
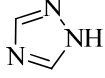
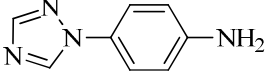
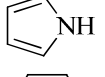
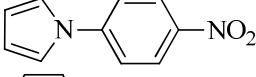
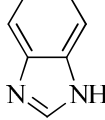
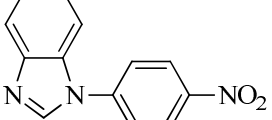

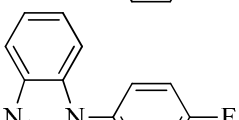
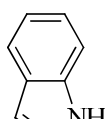
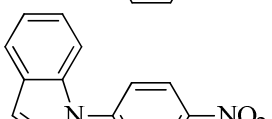
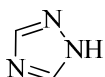
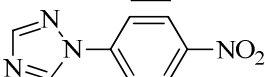
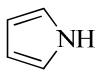
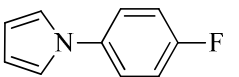
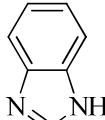
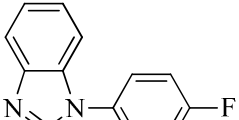
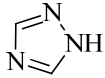
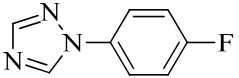
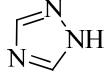
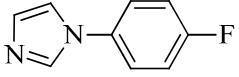
Table 7. Pd/ZnO nanoparticles catalyzed *N*-arylation Ullmann type cross-coupling reaction of benzimidazole with iodobenzene^a




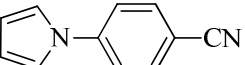

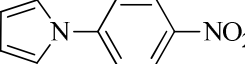
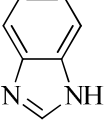
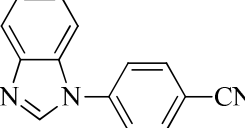
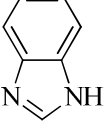
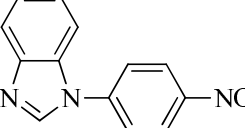
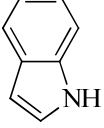
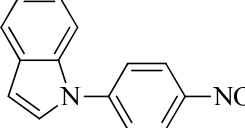
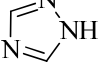
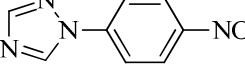

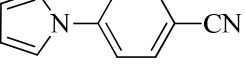

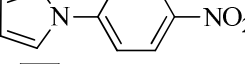
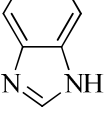
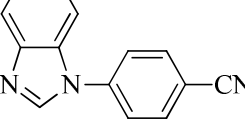
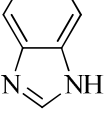
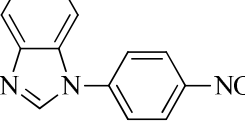
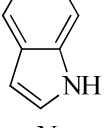
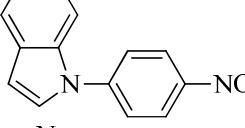
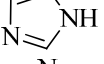
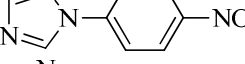
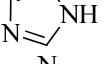
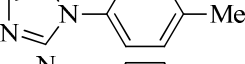
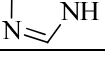
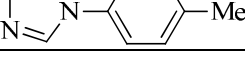
Entry	Pd/ZnO nanoparticles (g)	Base	Solvent	Yield (%) ^b
1	0.0005	K ₂ CO ₃	DMF	63
2	0.001	K ₂ CO ₃	DMF	78
3	0.003	K ₂ CO ₃	DMF	95
4	0.005	K ₂ CO ₃	DMF	95
5	none	K ₂ CO ₃	DMF	0
6	0.003	K ₂ CO ₃	none	93
7 ^c	0.003	K ₂ CO ₃	EtOH	78
8	0.003	K ₂ CO ₃	DMSO	73
9	0.003	K ₂ CO ₃	H ₂ O	73
10 ^c	0.003	K ₂ CO ₃	CH ₃ CN	51
11	0.003	K ₂ CO ₃	PhCH ₃	43
12	0.003	K ₃ PO ₄	DMF	95
13	0.003	Cs ₂ CO ₃	DMF	88
14	0.003	Na ₂ CO ₃	DMF	83

^a Reaction conditions: 1*H*-benzo[*d*]imidazole (1 mmol), iodobenzene (1 mmol), Pd/ZnO nanoparticles, base (1 mmol), and solvent (1 mL) at 120 °C for 10 h. ^b Isolated yield. ^c Reaction conducted at 90 °C.

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4	C ₆ H ₅	I			5	95
5	C ₆ H ₅	I			5	92
6	4-Me-C ₆ H ₄	I			5	90
7	4-OMe-C ₆ H ₄	I			9	92
8	4-OMe-C ₆ H ₄	I			7	90
9	4-Me-C ₆ H ₄	I			6	90
10	4-NH ₂ -C ₆ H ₄	I			8	90
11	4-NO ₂ -C ₆ H ₄	I			4	98
12	4-NO ₂ -C ₆ H ₄	I			6	95
13	4-F-C ₆ H ₄	I			6	93
14	4-NO ₂ -C ₆ H ₄	I			5	97
15	4-NO ₂ -C ₆ H ₄	I			4	97
16	4-F-C ₆ H ₄	Br			5	95
17	4-F-C ₆ H ₄	Br			8	94
18	4-F-C ₆ H ₄	Br			7	92
19	4-F-C ₆ H ₄	Br			4	90

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20	4-CN-C ₆ H ₄	Br			5	96
21	4-NO ₂ -C ₆ H ₄	Br			5	94
22	4-CN-C ₆ H ₄	Br			8	95
23	4-NO ₂ -C ₆ H ₄	Br			8	90
24	4-NO ₂ -C ₆ H ₄	Br			6	92
25	4-NO ₂ -C ₆ H ₄	Br			6	93
26	4-CN-C ₆ H ₄	Cl			7	92
27	4-NO ₂ -C ₆ H ₄	Cl			7	93
28	4-CN-C ₆ H ₄	Cl			10	92
29	4-NO ₂ -C ₆ H ₄	Cl			8	90
30	4-NO ₂ -C ₆ H ₄	Cl			8	90
31	4-NO ₂ -C ₆ H ₄	Cl			8	87
32	4-Me-C ₆ H ₄	Br			9	70
33	4-Me-C ₆ H ₄	Cl			13	70

^a Isolated yield.

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Conclusions

In conclusion, we have successfully prepared Pd supported on ZnO nanoparticles as heterogeneous catalyst for *O/N*-arylation reactions without using any ligands and Ar or N₂ flow under air atmosphere. In this work, the palladium catalyst exhibited excellent activities for the C-O and C-N bond cross-coupling reactions. Moreover, the easy extractive recovery of the final product, and the solid residue showing catalytic activity can be reused several times can also be considered as strong practical advantages of this method. This methodology will provide a facile, efficient, and environmentally friendly process for the C-O and C-N bond cross-coupling reactions because of its wide applicability to various sensitive substituents (i.e., MeCO, CN, and NH₂), without the requirement of protection on these functional groups, and the use of less toxic reagents.

Experimental Section

The amount of palladium nanoparticles supported on ZnO was measured by ICP analyzer (Varian, Vista-pro) and atomic absorption spectroscopy. The distribution morphology of the product was analyzed by Leica Cambridge, models 360, version V03.03 scanning electron microscope (SEM) and the size of the nano particles was confirmed by a Philips CM10 TEM instrument. X-ray photoelectron spectroscopy (XPS) measurements were conducted with a XR3E2 (VG Microtech) twin anode X-ray source using AlK α =1486.6 eV). The specific surface areas (SSA_{BET}; (m²/g)) of the nanopowders were determined with the nitrogen adsorption measurement applying the BET method at 77 K (BELsorp-mini II). A lab-made thermogravimetric analyzer (TGA) was also adopted for studying both the interaction behavior of CO (Linde, 99.99%) as a selective probe molecule with palladium nanoparticles and thermal stability of Pd-supported ZnO nanoparticles after interacted with CO molecules.²⁴ ¹H and ¹³CNMR spectra were obtained on a Bruker DPX 250 MHz instrument.

Synthesis of Pd/ZnO nanoparticles

Pd/ZnO nanoparticles catalyst was prepared by co-precipitation (CP) method. Zn(NO₃)₂·6H₂O (0.267 g, 0.897 mmol), was dissolved in 25 mL distilled water to obtain a certain concentration solutions. Also Pd(NO₃)₂·2H₂O (0.0266 g, 0.099 mmol) was dissolved in 25 mL distilled water and sonicated to obtain a uniform solutions. Then the corresponding mixed nitrate solutions of palladium and zinc were precipitated with 1M sodium carbonate solution at room temperature to produce a final pH of 8. After aging for 2 h at 70-80 °C, the precipitates were filtered, washed several times with distilled water,

dried at 80 °C overnight and then calcined at 723 K for 2 h. Palladium coating was 9.84 wt% as measured by ICP.

Synthesis of ZnO nanoparticles

ZnO nanoparticles catalyst was prepared by co-precipitation (CP) method. Zn(NO₃)₂·6H₂O (0.267 g, 0.897 mmol), was dissolved in 25 mL distilled water to obtain a certain concentration solutions. Then the corresponding nitrate solution of zinc was precipitated with 1M sodium carbonate solution at room temperature to produce a final pH of 8. After aging for 2h at 70-80 °C, the precipitate was filtered, washed several times with distilled water, dried at 80 °C overnight and then calcined at 723 K for 2 h.

General procedure for *O*-arylation reaction

In the typical procedure *O*-arylation coupling reaction, a mixture of arylhalide (1mmol), phenol (1 mmol), K₂CO₃ (1 mmol), and Pd/ZnO nanoparticles (0.005 g, which contains 462×10⁻⁸ mol% of Pd which was determined by ICP) at 120 °C was placed in a round bottom flask. The progress of reaction was monitored by TLC. After completion of the reaction, the reaction mixture was diluted with ethyl acetate (5 mL) and then centrifuged to separate the catalyst. The solvent was removed under reduced pressure to get the crude product. The crude product was purified by column chromatography to afford the pure product.

General procedure for *N*-arylation reaction

A mixture of arylhalide (1mmol), *N*-H heterocycle (1.0 mmol), K₂CO₃ (1 mmol), DMF (1 mL), and Pd/ZnO nanoparticles (0.003 g, which contains 277×10⁻⁸ mol% of Pd which was determined by ICP) at 120 °C was placed in a round bottom flask. Progress of the reaction was monitored by TLC. After the reaction was finished, it was cooled to the room temperature, and DMF was removed under reduced pressure. The residue was diluted with ethyl acetate (5 mL), and centrifuged to separate the catalyst. The centrifugate was washed with water (2×5 mL), dried over anhydrous Na₂SO₄, filtered, and concentrated. Further purification was achieved by column chromatography.

All compounds are known and were characterized by comparison of their physical and spectroscopic data with the already described in the literatures.

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Notes and references

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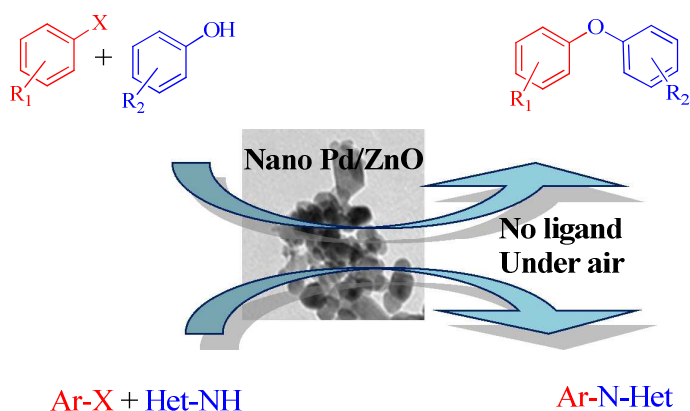
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Graphical abstract

Highly Active Recyclable Heterogeneous Pd/ZnO Nanoparticles Catalyst: Sustainable Developments for the C-O and C-N Bond Cross-Coupling Reactions of Aryl Halides Under Ligand-Free Condition

Mona Hosseini-Sarvari *, and Zahra Razmi

A novel Pd supported on ZnO nanoparticles for C-O and C-N bond cross-coupling reactions under ligand-free condition.



X= I, Br, Cl
Ar= Aryl
Het-NH= HN-Heterocycles