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Preparation of a titania-supported highly dispersed palladium nano-catalyst and its application in Suzuki and Heck coupling reactions

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In this work, palladium complexes nanoparticles in titania are prepared by a pH-controlled adsorption and without pH-controlled adsorption method. This method results in high-dispersion palladium on the titania surface. We demonstrate the use of the titania-supported palladium as an efficient catalyst for Suzuki and Heck reactions of a representative range of aryl bromides and chlorides. The reusability of catalyst was tested, and deactivation process of the catalyst was not observed after four recycles. The catalysts were characterized by FT-IR, NMR, elemental analysis, field emission scanning electron microscopy, transmission electron microscopy and X-ray diffraction. Copyright © 2013 John Wiley & Sons, Ltd.

Keywords: titania; Suzuki reaction; Heck reaction; adsorption method; nano-catalyst

Introduction

The transition metal-catalyzed cross-coupling reaction for the formation of carbon–carbon bonds has recently appeared as a modern method in organic synthesis.[1–3]The palladium-catalyzed coupling of aryl halide with arylboronic acid has evolved into one of the most important and successful methods for forming biaryls.[4,5] In recent years, the development of ligands has afforded highly active palladium catalysts for Suzuki reactions.[6] However, homogeneous catalytic systems have their own shortcomings. For example, the separation processes are usually complex.[7,8] Theoretically, supported palladium catalysts having high activity offer several noteworthy practical advantages in synthetic and industrial chemistry. Among those, easy separation of the catalyst from the desired reaction product and easy recovery and reuse of the catalyst are important.[9] An assortment of solid materials as supports has been used to support palladium species. Several MCM-41-supported ligand-free Pd as efficient catalysts for Heck reactions of aryl bromides with styrene and methyl acrylate under aerial conditions have been reported.[10] More recently, Oyamada *et al*. have studied the hydrogenation reaction of C–C double and triple bonds in a range of substrates using a continuous-flow system with polysilane-supported palladium/alumina (Pd(PSi/Al_2O_3)) hybrid catalyst.[11] Also, Polshettiwar *et al*.[12] and Modak *et al*.[13] demonstrated the activity of several silica-supported Pd catalysts in a variety of coupling reactions (e.g. Suzuki, Heck, Sonogashira). Moreover, Ambulgekar and co-workers carried out the Heck reaction of iodobenzene with methyl acrylate using Pd/C as catalyst in the presence of ultrasound at ambient temperature.[14] In addition, polymeric materials as supports have been successfully utilized in synthesizing catalysts for coupling reactions.[15–17] The highly dispersed catalyst increases catalytic activity and reusability, which would allow use of low palladium loading for reducing the cost of products in large-scale processes. TiO_2 usually shows pH-dependent surface charges when immersed in aqueous solution because of the existence of Ti-OH on the surface.[18] The absorption of TiO_2 relies on an environment of different pH value. In the present study, we report the preparation of highly dispersed palladium complexes in TiO_2 by the adsorption method for the Suzuki and Heck coupling reactions. Palladium complex **1** was reported in our previous work[19] and **2** was synthesized by the method reported in our previous paper[20] and well characterized. Furthermore, we indicate that the heterogeneous catalyst **2**/TiO_2 can be used in Suzuki and Heck reactions utilizing various aryl halides and recovered and reused four times without loss of activity in the Suzuki reaction of bromobenzene with phenylboronic acid. The dispersed palladium complexes in TiO_2 are shown in Fig. 1.

Experimental

Materials and Techniques

All chemicals such as commercial titania P-25, solvent and other chemicals were purchased from Merck and Aldrich. Conversions were monitored using an Agilent 6890N gas chromatograph equipped with a capillary HP-5$^+$ column, based on aryl halides. The column properties were: 30 m length, 0.32 mm internal diameter and 0.25 μm film thickness. A Hitachi S4160 field

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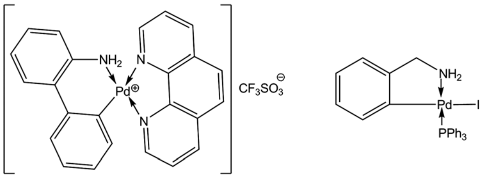


1 2

Figure 1. The structures of dispersed palladium complexes.

emission scanning electron microscope was employed to show nano dimensions. Powder X-ray diffraction (XRD) patterns were recorded on a Philips X'Pert diffractometer with Cu Kα radiation at 40 kV and 30 mA, with a scan speed of 2° min^{-1} and a range of 2θ from 5° to 80°. The morphology, structure and energy-dispersive spectroscopy (EDS) of catalyst were analyzed on a JSM2100F transmission electron microscope with an EDS spectrometer. The sample for transmission electron microscopy (TEM) was prepared by placing a drop of the suspension in ethanol on to a continuous carbon-coated copper TEM grid and drying at room temperature under atmospheric pressure.

Catalyst Preparation

Synthesis of palladium complexes

Synthesis of complex **1** has been reported previously..[19] Besides, complex **2** was prepared by the method reported in our earlier work.[20]

2: Yield 93%; m.p. 180–184. Elemental analysis calcd for $C_{25}H_{23}NIPPd$: C, 49.90; H, 3.85; N, 2.33. Found: C, 49.79; H, 3.76; N, 2.41%. IR (KBr, cm^{-1}); $_a$ (N-H) 3223, $_s$ (N-H) 3161. ^{1}HNMR (300 MHz, ppm, $CDCl_3$); $\delta = 4.02$ (brs, 2H, CH_2), 4.23(brs, 2H, NH_2), 6.37 (m, 2H, C_6H_4), 6.82 (t, 1H, C_6H_4, $^3J_{HH} = 6$ Hz), 6.95 (d, 1H, C_6H_4, $^3J_{HH} = 6$ Hz), 7.30 (m, 9H, $3C_6H_5$), 7.69 (m, 6H, $3C_6H_5$). ^{13}CNMR (100 MHz, $CDCl_3$, ppm); $C_{aliphatic}$ $\{\delta = 49.2\}$, $C_{aromatic}$ $\{\delta = 120.05$, 120.29, 122.63, 123.76, 132.89, 137.10, 134.18, 134.30 (C_o, PPh_3, $^2J_{PC} = 16$), 125.71, 126.03, 129.71, 130.05, 135.54, 135.66 (C_i, PPh_3, $^1J_{PC} = 40$)$\}$. ^{31}PNMR (300 MHz, $CDCl_3$, ppm): 42.21.

Nano-catalyst preparation

2/TiO_2 catalyst was prepared according to the adsorption method by following the literature.[18] 0.68 g TiO_2 was added to 60 ml aqueous solution of **2** (0.01 mol l^{-1}). pH was adjusted 1.5 by 2 M HCl aqueous solution and the suspension was vigorously stirred for 6 h at room temperature. By filtration of the suspension after adsorption, the powdery solid was separated and washed with a large amount of water several times. Then powdery solid was dried at 100°C. To prepare **1**/TiO_2 this process was done using **1** without pH adjustment.

Catalytic Reactions

In the Suzuki reaction, 0.02 g (0.12 mol% Pd) **1**/TiO_2 or **2**/TiO_2 as heterogeneous catalyst, 0.5 mmol aryl halide, 0.75 mmol phenylboronic acid and 1.5 mmol base were added to a balloon, followed by addition of methanol 8 ml. The mixture was stirred in a pre-heated oil bath. In the Heck reaction, a round-bottom flask was charged with 0.5 mmol aryl halide, 0.75 mmol alkene, 1.5 mmol base, 8 ml methanol, 0.02 g **1**/TiO_2 or **2**/TiO_2 as catalyst. The mixture was stirred in a pre-heated oil bath. After the reactions were completed, the solid catalyst was separated by centrifuge, washed with water several times to eliminate base and solid, washed with acetone to eliminate adsorbed organic substrate and dried at 100°C. The product of the reaction blend was analyzed by GC. Also, the products were characterized by comparing their melting points, ^{1}H and ^{13}C NMR spectra with those found in the literature.[21]

Results and Discussion

XRD Pattern

Powder XRD analysis confirmed that the TiO_2 nanoparticles were in the anatase phase in comparison with standard diffractions from JCPDS card 21-1272. In the case of **1**/TiO_2, the XRD pattern indicated that the amount of metallic Pd was less than 3%, verifying complex **1** coated on the TiO_2 (Fig. 2).

Field Emission Scanning Electron Microscopy (FESEM) Microstructure

The FESEM images showed catalysts with nanoparticles. The surface morphology of the catalysts has also been investigated. It was indicated that palladium complex **1** was agglomerated on the TiO_2, which was synthesized without pH adsorption method (Fig. 3a). But in the case of **2**/TiO_2, it was verified that pH adsorption method played an important role in the distribution of nanoparticles (Fig. 3b).

Transmission Electron Micrsoscopy (TEM) Microstructure and Energy-Dispersive Spectroscopy (EDS)

To study the possible reason for the different catalytic performance of the catalysts, the surface morphology of the catalysts was also characterized by TEM. A series of TEM figures were taken from **1**/TiO_2 and **2**/TiO_2 catalysts before use in the Suzuki and Heck reactions, and are presented in Fig. 4(a) and (b) respectively, which indicate size distribution and EDS spectra of the isolated catalyst. Evidently, highly dispersed spherical palladium complex nanoparticles of size 5–20 nm on the TiO_2 surface were observed.

EDS provides an elemental analysis of the samples, showing the presence and relative distribution of the present

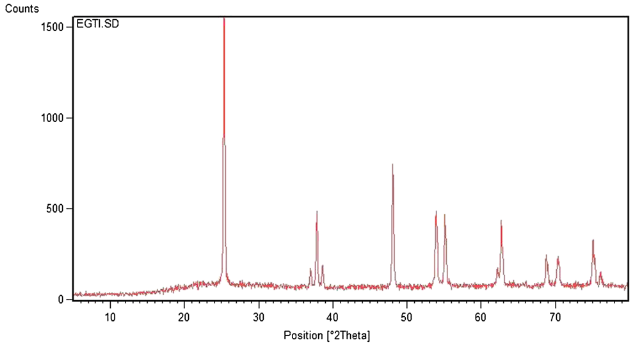


Figure 2. Powder XRD profile of **1**/TiO_2 nanoparticle.

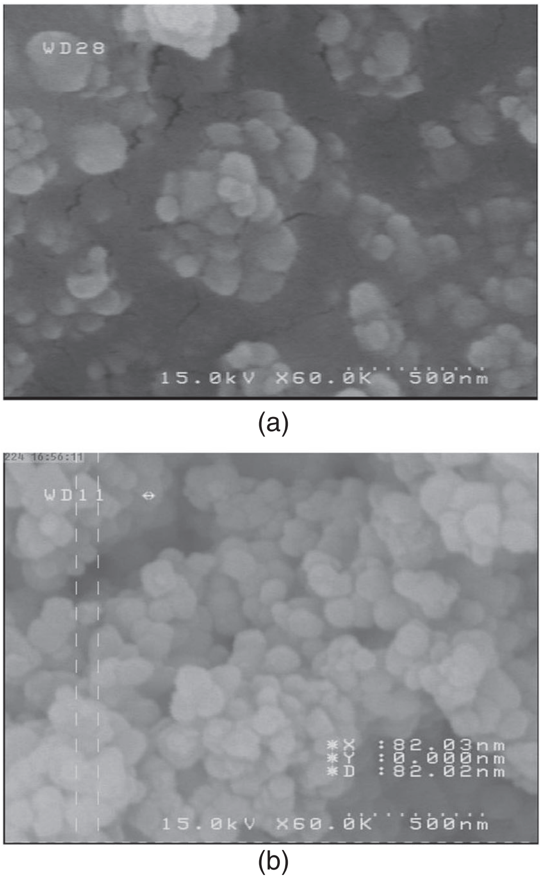


Figure 3. SEM image of (a) **1**/TiO_2 and (b) **2**/TiO_2.

elements. The EDS spectrum, Fig. 4(a) (**1**/TiO_2) and (b) (**2**/TiO_2), obtained for palladium complex/TiO_2 catalyst indicates successful deposition of the palladium complex nanoparticles on the titania surface.

Cross-Coupling Reactions

In the beginning, the Suzuki reaction of bromobenzene and phenylboronic acid was chosen as a model reaction to test the catalysts **1**/TiO_2 and **2**/TiO_2. Derived from our previous results,[22] we chose MeOH as the solvent, Na_2CO_3 and $K_3PO_4.3H_2O$ as the bases and 65°C as the reaction temperature. Since the reactions were not completed in 1 h, the reaction time was increased up to 7 h. To evaluate the role of the pH-controlled adsorption method, **2**/TiO_2 was prepared by this method and **1**/TiO_2 was prepared without this method.

To assess the catalytic reactivity of **2**/TiO_2, we performed a number of Suzuki reactions of phenylboronic acid with several aryl bromides (Table 1, entries 1–6). Aryl bromides with electron-withdrawing substituents reacted smoothly (Table 1, entries 1–3). Considering the steric effect, aryl bromides with *ortho* substituents, e.g. 2-bromotoluene and 2- bromoaniline, provided the corresponding products in high yields (Table 1, entries 5 and 6). Conversely, in the presence of **1**/TiO_2, Suzuki reaction of bromobenzene with phenylboronic acid did not proceed well (Table 1, entry 7). This result, with respect to the reaction conditions, showed that the catalytic reactivity of **1**/TiO_2 was not as satisfactory as complex **1** in the similar reaction in homogeneous media.[22] Referring to our previous report,[22] **1** did not show high catalytic activity in homogeneous media. Also, the reaction of bromobenzene with phenylboronic acid (Table 1, entry 7) and iodobenzene with styrene (Table 2, entry 1) using **1**/TiO_2 did not proceed well. Hence we stopped applying this catalyst in the coupling reactions. For catalytic activity of complex **2**, several Suzuki reactions of reactive and unreactive aryl bromides were carried out (Table 1, entries 10–14). It was revealed that **2**/TiO_2 had better performance than **2** in the coupling reactions (Table 1). The results verified that, apart from the rate of reactivity of complexes **1** and **2**, the pH-controlled adsorption method played an important role in the high catalytic performance of **2**/TiO_2 in the coupling reactions.

The reactivity of **2**/TiO_2 was also tested in Suzuki reactions of aryl chlorides with phenylboronic acid. Surprisingly, in spite of using sterically hindered aryl chlorides, bearing electron-donating groups, the yields of the reactions were promising (Table 1, entries 8–10). 4-bromoacetophenone and 2-bromotoluene did not react using only TiO_2 as catalyst (Table 1, entries 1 and 5).

For further investigations, the efficiency of **1**/TiO_2 and **2**/TiO_2 was also studied in Heck reactions (Table 2). Similar to the Suzuki reaction, the catalytic performance of **1**/TiO_2 in the Heck reaction of iodobenzene with styrene was poor (Table 2, entry 1). However, relating to the low C-I bond strength compared with C-Br, iodobenzene was used instead of bromobenzene.

The coupling of styrene and methyl acrylate with a variety of aryl halides was also examined using **2**/TiO_2 as the catalyst. Good to excellent yields were gained, apart from the substituents of aryl halides.

The results demonstrate that in this case the Heck reaction could be utilized with aryl bromides and chlorides having different functional groups: cyano, amino, methyl, etc. (Table 2, entries 2–14). In addition, there was high catalytic activity in the reaction of 2-chlorotoluene with styrene using catalyst **2**/TiO_2 (Table 2, entry 12). With regard to alkenes, styrene served as an appropriate coupling partner (Table 2, entries 2, 4–6, 8–10, 12 and 13). Furthermore, based on Li *et al.*'s report,[18] it is concluded that PdO and $PdCl_2$ will not work in the Heck reaction as efficiently as **2**/TiO_2 under the reaction conditions employed in this work.

For further studies, more Suzuki reactions of aryl bromides were carried out in the presence of **1**/TiO_2 (Table 3). These reactions were much more difficult than those when **2**/TiO_2 was applied.

Also, to generalize the scope of the reactions, phenylboronic acid derivatives were utilized. The results are shown in Table 4.

In order to contrast, palladium complexes **1** and **2** were used instead of $PdCl_2$ in this work. In comparison with the catalyst reported previously,[18] the catalyst **2**/TiO_2 showed reactivity at lower reaction temperature and in shorter reaction times. In particular, aryl chlorides reacted much more smoothly (Table 2, entries 10–14).

It is well known that metal catalyst supported on titania exhibits the 'strong metal–support interaction' (SMSI) phenomenon. This is due to the decoration of the metal surface by an electron transfer between the support and the metals.[23,24] Thus, owing to the charge transfer from Ti species to Pd, it can be inferred that the reaction mechanism begins with a reduction step in which the Pd(I) complex is converted into the Pd(0) catalyst.

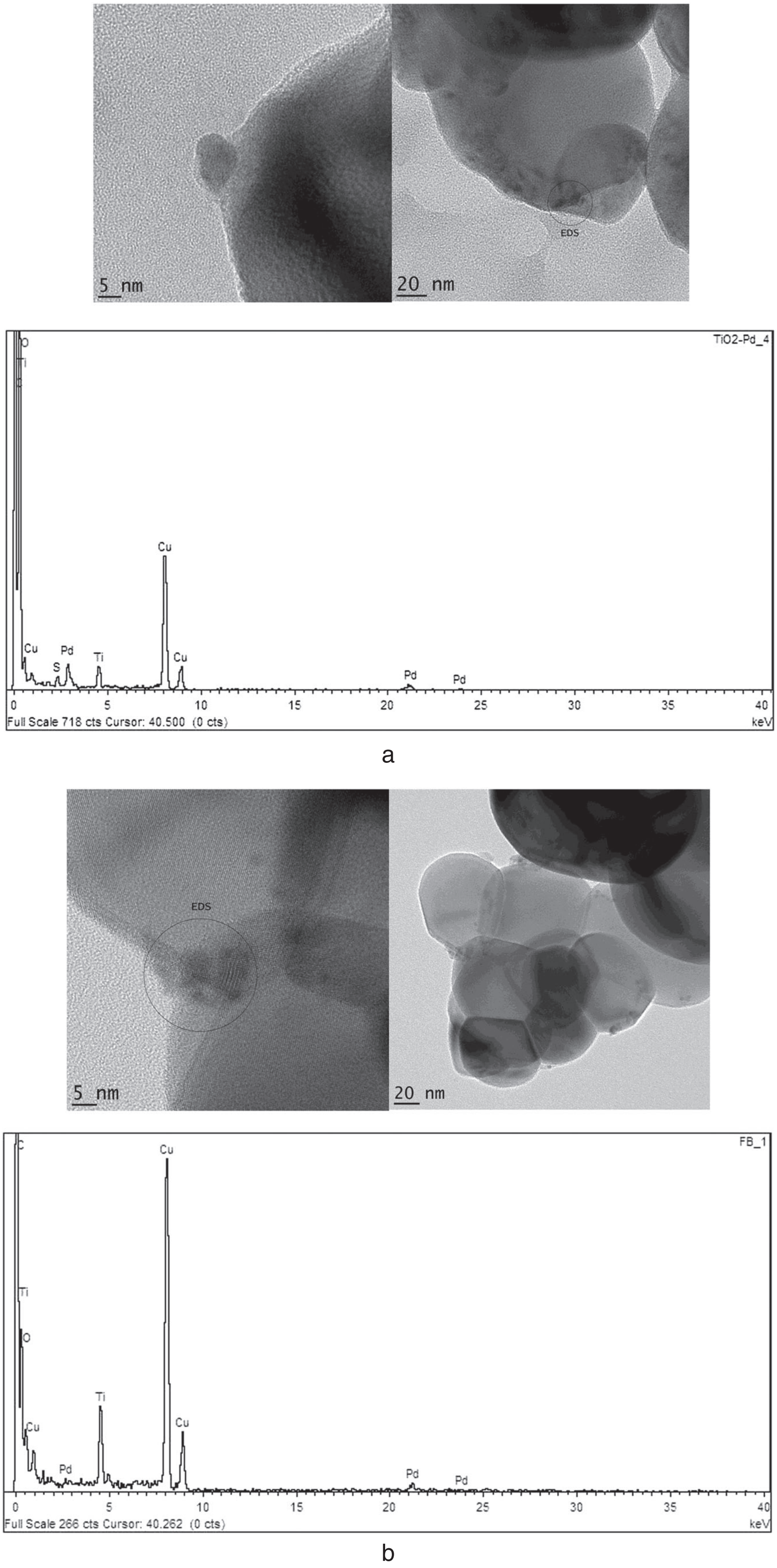
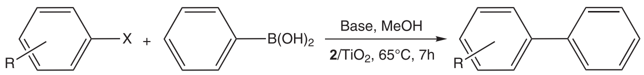


Figure 4. TEM image and EDS spectra of nano-catalysts (a) **1**/TiO_2 and (b) **2**/TiO_2.

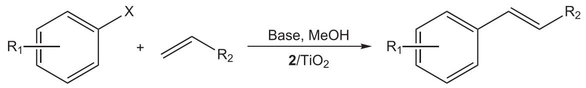
Table 1. The effect of catalyst on Suzuki reaction of aryl halides with phenylboronic acid[a]



Entry	R	X	Base	Yield (%)[b]
1	*p*-CH_3CO	Br	$K_3PO_4.3H_2O$	94, 0[c]
2	*p*-CN	Br	$K_3PO_4.3H_2O$	95
3	*p*-CF_3	Br	$K_3PO_4.3H_2O$	96
4	H	Br	Na_2CO_3	90
5	*o*-CH_3	Br	$K_3PO_4.3H_2O$	80, 0[c]
6	*o*-NH_2	Br	$K_3PO_4.3H_2O$	76
7	H	Br	Na_2CO_3	30[d]
8	H	Cl	Na_2CO_3	73
9	*o*-CH_3	Cl	$K_3PO_4.3H_2O$	64
10	*o*-NH_2	Cl	$K_3PO_4.3H_2O$	61
11	*p*-CH_3CO	Br	$K_3PO_4.3H_2O$	68[e]
12	H	Br	Na_2CO_3	64[e]
13	*o*-CH_3	Br	$K_3PO_4.3H_2O$	52[e]
14	*o*-NH_2	Br	$K_3PO_4.3H_2O$	48[e]

[a] Reaction condition: bromobenzene (0.5 mmol), phenylboronic acid (0.75 mmol), catalyst (0.12 mol% Pd), Na_2CO_3 (1.5 mmol), MeOH (8 ml).
[b] Isolated yields (average of two experiments).
[c] Only TiO_2 was used as catalyst.
[d] **1**/TiO_2 was used as catalyst.
[e] Complex **2** was used as catalyst.

Table 2. The effect of catalyst on Heck reaction of aryl halide with alkealkenes[a]



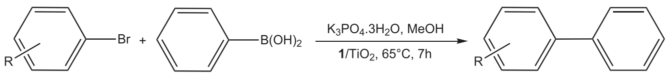
Entry	R_1	R_2	X	Base	Temp. (°C)/time (h)	Yield (%)[b]
1	H	Phenyl	I	Na_2CO_3	65/7	30[c]
2	*p*-CH_3CO	Phenyl	Br	$K_3PO_4.3H_2O$	65/10	93
3	*p*-CH_3CO	COOMe	Br	$K_3PO_4.3H_2O$	65/10	90
4	*p*-CN	Phenyl	Br	$K_3PO_4.3H_2O$	65/10	93
5	*p*-CF_3	Phenyl	Br	$K_3PO_4.3H_2O$	65/10	91
6	H	Phenyl	Br	Na_2CO_3	65/10	90
7	H	COOMe	Br	Na_2CO_3	65/10	86
8	*o*-CH_3	Phenyl	Br	$K_3PO_4.3H_2O$	65/10	82
9	*o*-NH_2	Phenyl	Br	$K_3PO_4.3H_2O$	65/10	76
10	H	Phenyl	Cl	Na_2CO_3	65/10	68
11	H	COOMe	Cl	Na_2CO_3	65/10	63
12	*o*-CH_3	Phenyl	Cl	$K_3PO_4.3H_2O$	65/10	58
13	*p*-CH_3CO	Phenyl	Cl	$K_3PO_4.3H_2O$	65/10	73
14	*p*-CH_3CO	COOMe	Cl	$K_3PO_4.3H_2O$	65/10	67

[a] Reaction conditions: aryl halide (0.5 mmol), alkene (0.75 mmol), catalyst (0.12 mol% Pd), base (1.5 mmol), MeOH (8 ml).
[b] Isolated yields (average of two experiments).
[c] **1**/TiO_2 was used as catalyst.

Reusability of the Catalysts

In this work, catalyst **2**/TiO_2 was applied in the reaction of bromobenzene with phenylboronic acid, giving 90% yield for the first cycle (Table 1, entry 4). As the lifetime and reusability of heterogeneous catalysts are significant aspects in coupling reactions, the catalyst was isolated from the reaction combination by centrifuge, washed and dried at 120°C for 2 h. The recovered catalyst was subsequently utilized in this reaction under similar conditions, giving 89% yield for the second and 87% yield

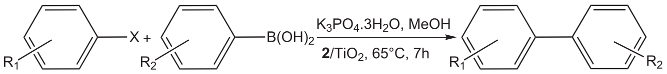
Table 3. The effect of catalyst on Suzuki reactions of aryl bromides with phenylboronic acid[a]



Entry	R	Yield (%)[b]
1	*p*-CH_3CO	28
2	*p*-CN	32
3	*o*-CH_3	5
4	*o*-NH_2	8

[a] Reaction conditions: aryl bromide (0.5 mmol), phenylboronic acid (0.75 mmol), catalyst (0.12 mol% Pd), Base (1.5 mmol), MeOH (8 ml).
[b] Isolated yields (average of two experiments).

Table 4. The effect of catalyst on Suzuki reactions of aryl halides with phenylboronic acid derivatives[a]



Entry	R_1	R_2	X	Yield (%)[b]
1	*p*-CH_3CO	*p*-CH_3O	Br	97
2	*p*-CH_3CO	*o*-CH_3	Br	89
3	*o*-CH_3	*p*-CH_3O	Br	86
4	*o*-CH_3	*o*-CH_3	Br	80
5	*p*-CH_3CO	*p*-CH_3O	Cl	78
6	*o*-CH_3	*o*-CH_3	Cl	62

[a] Reaction conditions: aryl halide (0.5 mmol), (*R*)-phenylboronic acid (0.75 mmol), catalyst (0.12 mol% Pd), base (1.5 mmol), MeOH (8 ml).
[b] Isolated yields (average of two experiments).

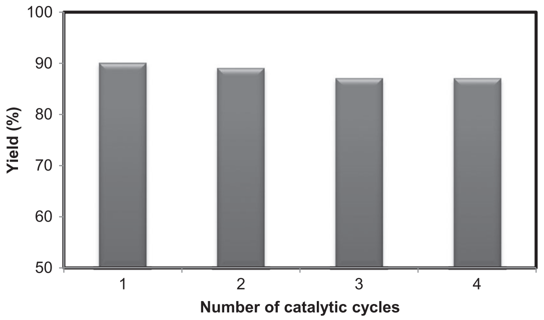


Figure 5. Recycling of **2**/TiO_2 catalyst in the Suzuki reaction between bromobenzene and phenylboronic acid.

for the third and forth runs (Fig. 5). Additionally, the catalyst **2**/TiO_2 was characterized by TEM after using four times. Its image (Fig. 6) demonstrated that palladium complex **2** nanoparticles did not agglomerate after four recoveries. Additionally, after reaction of bromobenzene with phenylboronic acid (Table 1, entry 4), the amount of palladium in the collected organic products solution was very low by ICP. Indeed, after recycling four times, leaching of palladium was trace. Moreover, it can be concluded that heterogeneous palladium is the catalytically active species.

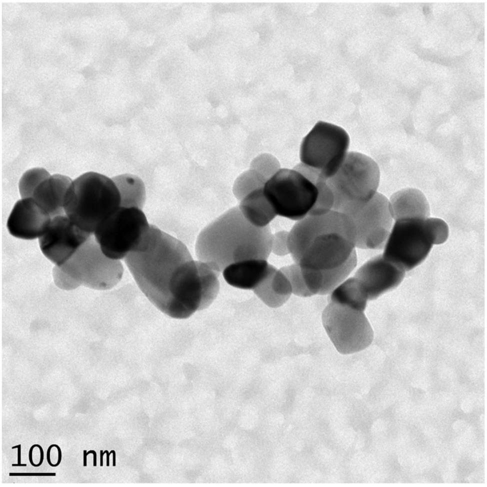


Figure 6. TEM image of nano-catalyst **2**/TiO_2 after four recoveries.

All these results suggest that preparing catalyst by pH adjustment method, as used in synthesis of **2**/TiO_2, results in creating smaller particles and consequently produces catalysts with high reactivity.

Conclusion

We prepared a capable palladium complex/TiO_2 catalyst, **2**/TiO_2, by a pH-controlled adsorption method. TEM images indicated nanoparticle of the catalyst. This catalyst showed a high activity and efficiency for Suzuki and Heck reactions using a range of activated and deactivated aryl halides. Also, different phenylboronic acid derivatives were used in order to check the generality. In order to assess, the catalyst can be simply retrieved and reused four times without losing catalyst activity.

Acknowledgment

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