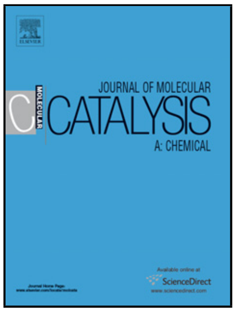


Title: Synthesis of polystyrene-supported Pd(II)-NHC complex derived from theophylline as an efficient and reusable heterogeneous catalyst for the Heck-Matsuda cross-coupling reaction

Author: Elmira Mohammadi Barahman Movassagh

PII: S1381-1169(16)30122-4
DOI: http://dx.doi.org/doi:10.1016/j.molcata.2016.03.045
Reference: MOLCAA 9844

To appear in: *Journal of Molecular Catalysis A: Chemical*

Received date: 5-1-2016
Revised date: 10-3-2016
Accepted date: 31-3-2016

Please cite this article as: Elmira Mohammadi, Barahman Movassagh, Synthesis of polystyrene-supported Pd(II)-NHC complex derived from theophylline as an efficient and reusable heterogeneous catalyst for the Heck-Matsuda cross-coupling reaction, Journal of Molecular Catalysis A: Chemical http://dx.doi.org/10.1016/j.molcata.2016.03.045

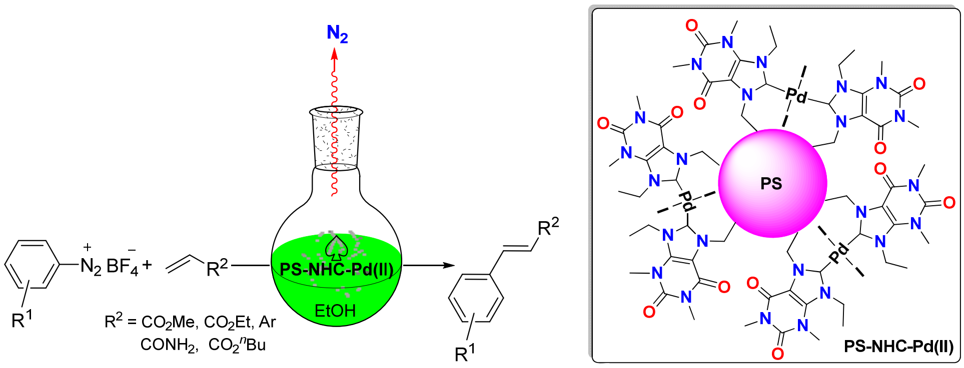
Synthesis of polystyrene-supported Pd(II)-NHC complex derived from theophylline as an efficient and reusable heterogeneous catalyst for the Heck-Matsuda cross-coupling reaction

Elmira Mohammadi, Barahman Movassagh*

Department of Chemistry, K.N. Toosi University of Technology, P.O. Box 16315-1618, Tehran, Iran; Tel: +98-21-23064323; Fax: +98-21-22853650

E-mail: bmovass1178@yahoo.com

Graphical abstract



Highlights

- A new polystyrene-supported Pd(II)-NHC catalyst based on theophylline was synthesized.
- Heck-Matsuda arylation of olefins with arenediazonium salts performed by the catalyst.
- Desired products obtained in good to excellent yields.
- The heterogeneous catalyst was reused for seven runs.

Abstract: The polystyrene-supported palladium(II)-N-heterocyclic carbene complex PS-NHC-Pd(II) was successfully synthesized from theophylline as an environmentally benign NHC precursor, using chloromethylated polystyrene resin. The PS-NHC-Pd(II) complex was characterized by various techniques including Fourier transform infrared spectroscopy (FTIR), energy dispersive X-ray spectroscopy (EDX), thermal analysis (TGA-DTG), inductively coupled plasma (ICP), and CHN elemental analysis. The morphology of the polymer beads was also studied using scanning electron microscope. The polymer supported Pd(II)-NHC complex exhibits excellent catalytic activity and stability for the Heck-Matsuda cross-coupling reaction under mild conditions. A variety of arenediazonium tetrafluoroborate salts was coupled with the olefinic substrates in ethanol, in the presence of the 0.9 mol% of the catalyst to afford the corresponding cross-coupling adducts in high yields under aerial conditions. Moreover, the heterogeneous catalyst can be easily recovered by simple filtration and reused for seven cycles without significant loss in its activity.

Keywords: N-Heterocyclic carbene, Heterogeneous catalyst, Theophylline, Polystyrene, Heck-Matsuda cross-coupling.

1. Introduction

Over the past decades, palladium-catalyzed transformations have proved to be powerful tools in both microscale laboratory and large scale syntheses [1]. Among various Pd-mediated bond-forming reactions developed to date, the cross-coupling of an aryl moiety with an olefin skeleton, referred to as the Heck reaction, is an important synthetic route since the resultant functionalized olefins are ubiquitous in numerous natural products [2], biologically active pharmaceuticals [3], and as precursor for materials science applications [4]. The traditional Mizoroki-Heck reaction involves a cross-coupling reaction between aryl and alkenyl halides and olefins. However, these reactions are strongly limited by harsh reaction conditions, low functional group tolerance, and high cost of the reagents. A breakthrough has been made by Matsuda and co-workers who utilized arenediazonium salts instead of aryl halides as the electrophilic coupling fragments [5]. The practical benefits of using arenediazonium salts over common electrophiles such as aromatic halides and triflates contribute the economic, environmental, and synthetic accessibility due to the fact that these species can be easily prepared from cheap and available aromatic amines in high yields [6]. Furthermore, the Heck-

Matsuda reaction is usually performed at lower temperatures (between 20-50 ºC) compared to that of the typical Mizoroki-Heck reaction. This is due to the high reactivity of the diazonium salts in comparison to aryl halides and evolution of the neutral nitrogen gas as the leaving group [6c, 7]. Moreover, in the presence of arenediazonium salts, the coupling reaction can be conducted under additive- and base-free conditions which expand the scope of the methodology to the substrates with sensitive functional groups [8]. Various homogeneous palladium catalysts have been designed for the cross-coupling reactions of the arenediazonium tetrafluoroborate salts with olefins [9]. However, limitations in terms of the recovery of the catalyst and contamination of the final product with toxic residues have lessened the utility of this class of catalysts in organic reactions. These shortcomings can be efficiently overcome by anchoring the palladium ions on suitable solid supports. Thus, diverse inorganic and organic solid supports for immobilizing Pd- species have been developed, including carbon nanotubes (CNTs) [10], silica-based supports [11], magnetic nanoparticles [12], polymers [13], bio-polymers [14], zeolites [15], molecular sieves [16], and metal oxides [17]. Among several kinds of polymers, chloromethylated polystyrene has attracted particular attention as potential supports for transition metal complexes due to the thermal stability, chemical inertness, low cost, and availability. In addition, metal species can be attached to the polymer matrix via covalent, or non-covalent bonding through ionic, hydrogen bond, or hydrophobic interactions [18]. Accordingly, many palladium complexes with different types of ligands, such as Schiff-bases [19], pincer-type ligands [20], N- and O-containing macrocyles [19a, 21], etc., that are anchored onto the polystyrene beads have found considerable synthetic applications. Therefore, designing or employing organic ligands with accessible binding sites has received a great deal of interest. In this context, N-heterocyclic carbenes (NHCs) are considered as an important class of ligands in inorganic and organometallic chemistry [22] ever since they were discovered by Arduengo's group [23]. Indeed, NHCs were first recognized as air- and moisture-stable phosphine mimics, but further studies revealed that NHC-metal complexes are superior to their phosphine-based counterparts in both activity and stability [24]. Moreover, NHCs have shown higher dissociation energies which enable them to bind to the metal ions regardless of their oxidation states [25]. Recently, polymer supported NHC-metal complexes, especially palladium complexes of these species, have been utilized in many organic reactions, including cross-coupling reactions [26], reductive amination of carbonyl compounds [27], and aminocarbonylation of aryl halides [28].

Despite the significant progress that has been made in the development of the NHC ligands based on which they can be immobilized on polymer matrix, there still exists a need for designing new, cheap, and environmentally benign N-heterocyclic carbenes. In this regard, using natural products as sustainable ligands has been growing increasingly. As shown in Fig. 1, caffeine and theophylline, which are the derivatives of xanthine and contain an imidazole ring in their structures, can be considered as highly-valued plant-derived precursors for the imidazolium-based N-heterocyclic carbenes. Major source of theophylline is cocoa beans, and caffeine is commonly found in the tea bush, coffee beans, and cola nuts. Previously, homogeneous bis-NHC-Pd catalyst based on caffeine has been reported by Luo and Lo in 2011, which suffers from the above-mentioned drawbacks of homogeneous catalysts [29].

Continuing our longstanding interest in developing efficient heterogeneous catalysts [30], herein we have designed a new Pd(II)-NHC catalyst which is derived from theophylline immobilized onto chloromethylated polystyrene as an efficient and recyclable catalyst for the Heck-Matsuda reaction. The catalyst is not only readily prepared from cheap reagents but also compatible with a wide variety of arenediazonium salts and olefins. Furthermore, this air-stable catalyst can be easily recovered from the reaction mixture by simple filtration.

2. Experimental

2.1. General remarks

All materials were commercial grade and purchased from Merck, Aldrich, and Fluka. Chloromethylated polystyrene resin cross-linked with 2% DVB (200-400 mesh, 2.8-3.2 mmol/g of Cl) was a product of Acros chemicals. Benzenediazonium tetrafluoroborate salt and its derivatives were all known and prepared by a previously described method [6]. The NBP test procedure was applied according to the literature [30]. FTIR spectra were recorded using an ABB Bomem model FTLA 2000 spectrophotometer. ^{1}H (300 MHz) and ^{13}C NMR (75 MHz) spectra of the final Heck-Matsuda products were recorded on Bruker AQS-300 Avance spectrometer. Thermogravimetry analysis and differential thermogravimetry analysis were carried out, using a thermal gravimetric analysis instrument (NETZSCH STA 409 PC/PG) under nitrogen atmosphere. The metal content of the catalyst was determined with Varian Vista-MPX inductively coupled plasma (ICP) instrument. The surface morphology of the polystyrene supported species was analyzed by scanning electron microscope (Vega, TESCAN-Model) equipped with energy dispersive X-ray (EDX) facility. The CHN analysis was carried out, using a Perkin-Elmer, 2004 (II) elemental analyzer. X-ray photoelectron spectroscopy (XPS) was performed with 8025-BesTec twin anode XR3E2 X-ray source system. The complete characterizations of the catalyst (**3**) and the NMR spectra of the selected compounds which are shown in Table 3 are actually given in electronic supporting information (ESI).

2.2. Preparation of the catalyst

*2.2.1. Preparation of polymer supported theophylline (PS-theo, **1**)*

In a 100 mL round-bottom flask, chloromethylated polystyrene resin (1.0 g, almost 3 mmol Cl) was allowed to swell in DMSO (20 mL) for 24h prior to the reaction. Then, theophylline (1.08 g, 6 mmol) and K_2CO_3 (0.90 g, 6.5 mmol) were added to the flask. The mixture was stirred at 70 ºC for 72h. Then, polymer beads were filtered and washed with hot DMSO (10 mL), hot DMSO:H_2O (1:1, 20 mL), hot H_2O (10 mL), MeOH (20 mL), and CH_2Cl_2 (10 mL) and dried in an oven for 5h.

*2.2.2. Synthesis of IL type species (PS-IL, **2**)*

The obtained PS-theo beads were swollen in CH_3CN (2 mL) for 4h; then, a solution of iodoethane (3 mL) in CH_3CN (1 mL) was added. The mixture was stirred at room temperature for 20h. The resulting beads were filtered and washed with CH_3CN (20 mL), and CH_2Cl_2 (20 mL), respectively, and dried in an oven at 100 ºC for 12h.

*2.2.3. Preparation of polymer anchored Pd(II)-NHC complex (PS-NHC-Pd(II), **3**)*

The functionalized beads (**2**, 0.6 g) were allowed to swell in dry THF (15 mL) for 1h; then, $Pd(OAc)_2$ (0.075 g, 0.33 mmol) was added to the above suspension. The solution was heated to 40 ºC for 16h. Afterwards, the resin was filtered and rinsed with THF (10 mL) and methanol (15 mL). The final polymer beads were dried in an oven at 80 ºC for 5h.

2.3. General procedure for the Heck-Matsuda cross-coupling reaction

A test tube was charged with arenediazonium tetrafluoroborate salt (0.5 mmol), PS-NHC-Pd(II) complex (**3**) (0.9 mol%, 15 mg), and EtOH (1 mL). To this mixture an olefin substrate (0.75 mmol) was added; the mixture was stirred at room temperature for an appropriate time. The progress of the reaction was monitored by TLC. After the completion of the reaction, the mixture was filtered to recover the catalyst and the filtrate was concentrated in a vacuum. Further, the reaction mixture was extracted with CH_2Cl_2 (2 × 5 mL) and the combined organic layer was washed with water (2 × 5 mL). The organic layer was dried over Na_2SO_4 and the solvent evaporated under reduced pressure. The residue was purified by preparative thin layer chromatography plate, using 10% EtOAc in *n*-hexane as eluent.

3. Results and discussion

3.1. Synthesis and characterization of catalyst

The steps involved in the synthesis of polystyrene resin (PS) supported Pd(II)-NHC catalysts have been outlined in Scheme 1. Firstly, a mixture of commercially available chloromethylated polystyrene (CMPS) resin and theophylline was heated in the presence of DMSO and K_2CO_3 at 70 ºC for 72h to produce the corresponding PS-theo (**1**). Respective treatment of polymer-bounded theophylline with iodoethane in acetonitrile in 3:1 ratio for 20h at room temperature afforded the immobilized ionic liquid (IL) type species PS-IL (**2**) as the NHC ligand precursor. Reaction of PS-IL (**2**) with $Pd(OAc)_2$ in dry THF for 16h at 40 ºC resulted in the covalent attachment of palladium (II) and the formation of PS supported NHC-Pd(II) complex **3**. In order to directly form imidazolium type IL and shorten the reaction pathway, caffeine was also selected to react with CMPS; the reaction was performed in DMSO at 80 ºC for 5 days to form PS-caff (**4**). The subsequent reaction of **4** with $Pd(OAc)_2$ gave PS-NHC-Pd(II) (**5**). The immobilization of theophylline and caffeine onto the PS matrix was confirmed by FTIR analysis; IR spectra were recorded separately at different stages, and a comparative study was made (Fig. 2). The IR spectrum of CMPS exhibits two characterstic bands at 1261.93 and 670.54 cm^{-1}, which contribute to the stretching and bending vibrations of C−Cl group (Fig. 2a). They were practically unobservable after the functionalization of the polymer with theophylline (Fig 2b). New absorption bands at around 1711.6 and 1653.1 cm^{-1} due to the C═O bond and the C=N stretching vibration of imidazole ring, respectively, confirms the binding of the ligand species (Fig. 2b). The broad band at 3452.4 cm^{-1} contributes to the tertiary nitrogen group [31], supporting the formation of the supported imidazolium salt PS-IL (Fig. 2c). Furthermore, on complexation with palladium, a new peak at 1476.6 cm^{-1} may be assigned to the stretching vibration of metal-$C_{aromatic}$-$N_{imidazole}$ bond [32] in PS-NHC-Pd(II) complex (Fig. 2d). Additionally, in the IR spectrum of the PS-caff (**4**), the intensity of the C─Cl peaks were slightly decreased, confirming that most of the –CH_2Cl groups on the CPMS have remained intact (Fig. 2e).

In order to ascertain the functionalization of the polymer and confirm that no adsorption has occurred during the immobilization of the ligand molecules, 4-(4'-nitrobenzyl)pyridine (NBP) tests [33] were also applied to the PS-theo, PS-IL, and PS-caff species (Fig. 3). This colorimetric test has been developed by Luis et al., and enabled us to monitor the presence of chloride groups on the polymer structure in each step. As depicted in Fig. 3a, the color of the CMPS beads turned to deep purple under the NBP test conditions, which gave a positive result answer to the test. However, under the same conditions with PS-theo and PS-IL species, no change in color was observed, which indicates that most of the chloride groups have been substituted by theophylline (Fig. 3b and 3c). On the other hand, the result of the NBP test was positive for the PS-caff, showing the presence of numerous unreacted chloride groups on polymer matrix (Fig. 3d).

Also, elemental analysis was applied at the end of each step to confirm the immobilization of the corresponding NHC preligands. The results are summarized in Table 1. Based on the elemental analysis, the nitrogen content introduced into the polymer was 15.41 wt% (11.0 mmol/g), for the PS-theo (**1**) suggesting that 90-96% of the total chloride content has been substituted by theophylline (Table 1, entry 1), whereas for the PS-caff (**4**) only 4.21 wt% (3.0 mmol/g) of nitrogen was found, affirming that only trace amounts of chloride groups been replaced by caffeine molecules (Table 1, entry 4).

As shown in Table 1, the content of palladium incorporated into the polymer matrix was determined by inductively coupled plasma (ICP) for PS-NHC-Pd(II) (**3**) as well as PS-NHC-Pd(II) (**5**) species and was found to be 3.31 wt% (0.31 mmol/g) and 1.1 wt% (1.0 mmol/g) Pd, respectively (Table 1, entries 3 and 5). According to the above-mentioned results, theophylline in comparison to caffeine was more effectively immobilized into the polystyrene beads; therefore, it was selected for further studies.

The scanning electron micrograph (SEM) images of the polymer supported NHC ligand precursor (**2**) and Pd(II)-NHC (**3**) catalyst were recorded to examine the morphological changes that have occurred on the polystyrene beads (Fig. 4). It can be clearly observed that the cubic morphology of the PS-IL species (Fig. 4a) was changed after the complexation with palladium diacetate (Fig. 4c). Furthermore, energy dispersive X-ray spectroscopy (EDX) analysis data for the polymer anchored IL (**2**) and palladium catalyst, PS-NHC-Pd(II) (**3**), are shown in Fig. 4b and 4d, respectively. The EDX data also infers the attachment of theophylline and its corresponding imidazolium salt as well as palladium metal on the polymer matrix.

To investigate the thermal behavior of the PS-NHC-Pd(II) catalyst, thermogravimetric and differential thermal analysis (TG-DTA) were also carried out under nitrogen atmosphere (Fig. 5). The negligible weight loss of the catalyst on heating below 200 ºC might be attributed to the release of physisorbed water. Meanwhile, the DTG curve shows that the decomposition of the polymeric materials and the Pd(II)-NHC complex occurred in one step from 320 ºC to 460 ºC, which corresponds to the main weight loss. Furthermore, the peak at 405 ºC in the DTG curve exhibits that the fastest mass loss has happened at this temperature which indicates that the supported catalyst is thermally stable and can be easily used in a broad range of temperatures.

To study the structure of the PS-NHC-Pd(II) catalyst, X-ray photoelectron spectroscopy (XPS) analysis was employed (Fig. 6). C, N, O, I, and Pd were detected in the as-synthesized polymer supported Pd(II)-NHC complex (Fig. 6a). As shown in Fig. 6b, two prominent peaks at 337.12 eV and 342.48 eV can be readily assigned to Pd(II) $3d_{5/2}$ and $3d_{3/2}$, which correspond to Pd(II) ions in the PS-NHC-Pd(II) catalyst [34]. The shift of Pd(II) $3d_{5/2}$ of $Pd(OAc)_2$ binding energy peak from 338.7 eV to 337.1 eV confirms the formation of Pd(II)-NHC complex [35]. The spectrum of carbon 1s clearly shows the peaks of C═C, C−C, C═N, C−N−C, C═O, and carbene to Pd bonds at 284.5, 285.1, 286.0, 286.8, 287.5, and 288.0 eV, respectively (Fig. 6c) [36]. Fig. 6d, exhibits N 1s XPS spectra of the as-synthesized catalyst; the spectrum was divided into two components at binding energies of 399.2 and 401.2 eV, which can be attributed to the sp^2 and quaternary nitrogens, respectively [34a, 37].

3.2. Catalytic activity of the PS-NHC-Pd(II) (3) in Heck-Matsuda cross-coupling reaction

To investigate the potency of the polystyrene supported Pd(II)-NHC precatalyst, it was used in the Heck-Matsuda cross-coupling reaction. It is known that the catalytically active Pd(0) species can be generated in the presence of olefin molecules; thus, an excess of olefin (olefin : $ArN_2^+BF_4^-$ = 1.5:1) was used in all studies. Optimization of the reaction conditions, including the solvent, the catalyst loading, and the temperature were carried out for the reaction of benzenediazonium tetrafluoroborate (**7a**) and ethyl acrylate (**8a**) as model substrates. The role of the solvent was screened by testing different protic and aprotic solvents such as MeOH, EtOH, H_2O, THF, and CH_3CN. As can be seen in Table 2, the reaction was significantly affected by the nature of the solvent. It was observed that among all of the solvents employed, EtOH was found to be the best reaction medium and the corresponding product was obtained in 98% yield (Table 2, entry 4). However, performing the reaction in pure water or in the organic/aqueous cosolvent system delivered poor results (Table 2, entries 5 and 6). Next, we examined the effect of different catalyst concentrations on the Heck-Matsuda reaction. As illustrated in Table 2, while 0.9 mol% of the catalyst worked remarkably well (98%, Table 2, entry 4), the yield of the coupling adduct dropped to 84% when 0.7 mol% of the catalyst was used (Table 2, entry 8). Furthermore, utilizing 1.1 mol% of the heterogeneous PS- NHC-Pd(II) (**3**) had no significant effect on either the yield or the reaction rate (Table 2, entry 7). To determine the effect of the temperature, the reaction was performed at 40 ºC but no marked change in the rate of the reaction was observed (Table 2, entry 9). Additionally, the cross-coupling reaction with the *in situ* generated benzenediazonium tetrafluoroborate salt **6a** was examined. Due to the poor solubility of the salt in THF, low yield of the product was obtained (Table 2, entry 10). In order to compare the catalytic activity of PS supported NHC-Pd(II) complexes derived from caffeine **5** with the catalyst **3**, the coupling of three different arenediazonium tetrafluoroborate salts with ethyl acrylate (**7**) were studied. As seen from Table 3, the reaction of benzenediazonium tetrafluoroborate with **7** gave 80% of the olefinated product in 2.5h in the presence of the catalyst **5.** On the other hand, the yield of the reaction was dramatically decreased in the second run (59%), while the catalyst **3** successfully performed the second cycle (98%). Also, PS-NHC-Pd(II) (**5**) conducted the cross-coupling reaction of 4-methoxy- and 4-nitrobenzenediazonium tetrafluoroborates with ethyl acrylate (Table 4, entries 2 and 3), but exhibited lower catalytic activity than that of PS-NHC-Pd(II) (**3**) catalyst.

The efficiency of the reaction protocol described above encouraged us to extend our studies to different olefins and arenediazonium tetrafluoroborate salts; the results are outlined in Table 4. In all cases, the coupling between arenediazonium tetrafluoroborate salts bearing electron donating as well as electron withdrawing groups with acrylate substrates, proceeded readily to afford the corresponding products in 78-98% yields (Table 4, entries 1-14). Sterically demanding 2-methylbenzenediazonium tetrafluoroborate salt reacted smoothly with ethyl acrylate and acryl amide to give the corresponding product in 93% and 78% yields, respectively (Table 4, entries 4 and 14). The coupling reactions of arenediazonium salts containing a halogen substituent gave exclusively the Heck-Matsuda adducts (Table 4, entries 7, 10, and 17), and no typical Mizoroki-Heck coupling was observed. We also studied the coupling of diverse styrenes with arenediazonium salts under the optimized reaction conditions. Due to the poor reactivity of the styrene substrates, the yields of the coupling reactions were decreased (Table 4, entries 15-19). However, high yields were obtained for the arenediazonium salts, bearing strong electron withdrawing groups (Table 4, entries 16 and 19). Moreover, reaction of arenediazonium salts with internal olefins was investigated; for instance, reaction of ethyl crotonate with arenediazonium salt bearing electron withdrawing group, such as 4-nitrobenzenediazonium tetrafluoroborate under the same reaction conditions occurred slowly and afforded only 24% yield of the desired product.

3.3. Recyclability test

The reusability of a catalyst is an attractive attribute, mainly for commercial applications. Therefore, the recovery and recyclability of our catalyst was studied by conducting the reaction of phenyldiazonium tetrafluoroborate salt and ethyl acrylate under standard reaction conditions. After the completion of the reaction, which was monitored by thin layer chromatography (TLC), the catalyst was removed from the reaction media by filtration and washed thoroughly with water and ethanol. Then, it was allowed to dry in an oven at 80 °C for 1h. The catalyst activity was not considerably diminished even after 7 cycles (Fig. 7). The degree of the palladium leaching from the heterogeneous catalyst was also investigated after the first and eight cycles. After the separation of the catalyst by filtration, the palladium content of the filtrate was determined by ICP. At the end of the first run, only 0.2% of palladium was lost into the solution during the course of the reaction. The total leaching of palladium was also measured and it was found that 1.9% of palladium was lost after eight reaction cycles. The result of the leaching test confirmed the heterogeneous nature of the catalyst.

3.4. The plausible mechanism of the Heck-Matsuda reaction

The proposed mechanism for the Heck-Matsuda cross-coupling reaction has been depicted in Scheme 2 [38]. The catalytic cycle was started by the reduction of Pd(II) to the active Pd(0) species in the presence of the olefin substrate. Then, oxidative addition of the arenediazonium salt to Pd(0) generated complex **8**, and subsequent elimination of N_2 create a cationic $ArPd^+L_2$ species (**9**). As shown in Scheme 2, unlike a typical Mizoroki-Heck reaction, the Heck-Matsuda reaction occurs in a polar-cationic mechanism. The next step involves migratory insertion of the alkenyl substrate, followed by *syn* β-elimination to produce cationic palladium(II)-hydrido complex (**12**), which rapidly undergoes reductive elimination to reproduce the active catalyst.

4. Conclusion

In summary, we have successfully prepared a recoverable and heterogeneous PS-NHC-Pd(II) catalyst based on theophylline as an environmentally benign NHC precursor. In fact, theophylline in combination with polystyrene can be considered as a cheap solid support for recycling of the costly palladium metal. This catalyst shows high efficiency in the Heck-Matsuda arylation of olefins in EtOH at room temperature. This reaction is a synthetically useful method for syntheses of arylated olefins because of its tolerance of many functional groups, short reaction times, high yields, mild, and *nature*-friendly conditions. Furthermore, the catalyst could be reused for seven successive cycles without noticeable loss of its catalytic activity. These advantages make the PS-NHC-Pd(II) complex valuable for synthetic and environmental aspects.

Acknowledgements

This research was supported by the Research Council of the K. N. Toosi University of Technology. We also gratefully acknowledge Mr. Joseph Clarkson, University of British Columbia, and Dr. Sogand Noroozizadeh for editing the English content of this article.

References

[1] A. Dumrth, C. Lübbe, M. Beller, in: A. Molnár (Ed.), Palladium catalyzed coupling reactions, Wiley-VCH, Germany, 2012, pp 12-103.

[2] (a) L.E. Overman, D.J. Ricca, V.D. Tran, J. Am. Chem. Soc. 115 (1993) 2042–2044;

(b) G. Ren, X. Cui, E. Yang, F. Yang, Y. Wu, Tetrahedron 66 (2010) 4022–4028.

[3] (a) S. Bradamante, L. Barenghi, A. Villa, Cardiovasc. *Drug Rev.* 22 (2004) 169–188;

(b) B.B. Aggarwal, A. Bhardwaj, R.S. Aggarwal, N.P. Seeram, S. Shishodia, Y. Takada, Anticancer Res. 24 (2004) 2783–2840;

(c) B. Schmidt, N. Elizarov, R. Berger, F. Hölter, Org. Biomol. Chem. 11 (2013) 3674-3691.

[4] (a) S. Sengupta, S.K. Sadhukhan, S. Bhattacharyya, J. Guha, J. Chem. Soc. Perkin Trans. 1 (1998) 407–410;

(b) S. Sengupta, S.K. Sadhukhan, J. Chem. Soc., Perkin Trans. 1 (1999) 2235–2236.

[5] K. Kikukawa, T. Matsuda, Chem. Lett. (1977) 159-162.

[6] (a) M. Bu, T.F. Niu, C. Cai, Catal. Sci. Technol, 5 (2015) 830-834;

(b) G. Danoun, B. Bayarmagnai, M.F. Grünberg, L.J. Gooβen, Angew. Chem. Int. Ed. 52 (2013) 7972-7975;

(c) K. Selvakumar, A. Zapf, A. Spannenberg, M. Beller, Chem. Eur. J. 8 (2002) 3901-3906;

(d) M.P. Doyle, W.J. Bryker, J. Org. Chem. 44 (1979) 1572-1574.

[7] (a) H. Brunner, N. Le Cousturier de Courcy, J.-P. Genêt, Tetrahedron Lett. 40 (1999) 4815-4818;

(b) A. Roglands, A. Pla-Quintana, M. Moreno-Marias, Chem. Rev. 106 (2006) 4622–4643.

[8] (a) E.-i. Negishi, C. Copéret, S. Ma, S.-Y. Liou, F. Liu, Chem. Rev. 96 (1996) 365-394;

(b) R. Grigg, V. Longanathan, V. Santhakumar, V. Sridharan, A. Teasdale, Tetrahedron Lett. 32 (1991) 687-690.

[9] (a) N. Oger, F. Le Callonnec, D. Jacquemin, E. Fouquet, E. Le Grognec, F.-X. Felpin, Adv. Synth. Catal. 356 (2014) 1065-1071;

(b) N. Oger, M. d'Halluin, E. Le Grognec, F.-X. Felpin, Org. Process Res. Dev. 18 (2014) 1786-1801;

(c) I. Peñafiel, I.M. Pastor, M. Yus, Eur. J. Org. Chem. 2012 (2012) 3151-3156;

(d) F.-X. Felpin, E. Fouquet, C. Zakri, Adv. Synth. Catal. 350 (2008) 2559-2565;

(e) M. Dai, B. Liang, C. Wang, J. Chen, Z. Yang, Org. Lett. 6 (2004) 221-224;

(f) M.B. Andrus, C. Song, J. Zhang, Org. Lett. 4 (2002) 2079-2082.

[10] (a) D.V. Jawale, E. Gravel, C. Boudet, N. Shah, V. Geertsen, H. Li, I.N.N. Namboothiri, E. Doris, Catal. Sci. Technol. 5 (2015) 2388-2392;

(b) M.B.T. Cardoso, E. Lewis, P.S. Castro, L.M. Dantas, C.C.S. De Oliveira, M. Bertotti, S.J. Haigh, P.H.C. Camargo, Eur. J. Inorg. Chem. 2014 (2014) 1439-1445;

(c) M. Navidi, B. Movassagh, S. Rayati, Appl. Catal. A: Gen. 452 (2013) 24-28.

[11] (a) N. Oger, E. Le Grognec, F.-X. Felpin, Chem. Cat. Chem. 7 (2015) 2085-2094;

(b) Y. Ukisu, Reac. Kinet. Mech. Cat. 114 (2015) 385-394;

(c) B. Basu, S. Paul, Appl. Organomet. Chem. 27 (2013) 588-594;

(d) J. D. Webb, S. MacQuarrie, K. MacEleney, C.M. Crudden, J. Catal. 252 (2007) 97-109.

[12] (a) L.M. Rossi, N.J.S. Costa, F.P. Silva, R. Wojcieszak Green Chem. 16 (2014) 2906-2933;

(b) S. Akbayrak, M. Kaya, M. Volkan, S. Özkar, Appl. Catal. B: Environmental 147 (2014) 387-393;

(c) Q.M. Kainz, R. Linhart, R.N. Grass, G. Vilé, J. Pérez-Ramírez, W.J. Stark, O. Reiser, Adv. Funct. Mater. 24 (2014) 2020-2027;

(d) M.B. Gawande, P.S. Brancoa, R.S. Varma, Chem. Soc. Rev. 42 (2013) 3371-3393;

(e) Y. Jang, J. Chung, S. Kim, S.W. Jun, B.H. Kim, D.W. Lee, B.M. Kim, T. Hyeon, Phys. Chem. Chem. Phys. 13 (2011) 2512-2516.

[13] (a) B. Kodicherla, C.P. Perumgani, S. Keesara, M.R. Mandapati, Inorg. Chim. Acta 423 (2014) 95-100;

(b) V. Udayakumar, S. Alexander, V. Gayathri, Shivakumaraiah, K.R. Patil, B. Viswanathan, J. Mol. Catal A: Chem. 317 (2014) 111-117.

[14] (a) B. Movassagh, N. Rezaei, New J. Chem. 39 (2015) 7988-7997;

(b) A. Kumbhar, R. Salunkhe, Curr. Org. Chem. 19 (2015) 2075-2121;

(c) K.R. Reddy, N.S. Kumar, P.S. Reddy, B. Sreedhar, M.L. Kantam, J. Mol. Catal. A: Chem. 252 (2006) 12-16;

(d) J. Xiao, Z. Lu, Z. Li, Y. Li, Appl. Organomet. Chem. 29 (2015) 646-652.

[15] (a) O.B. Ayodele, H.F. Abbas, W.M.A.W. Daud, Energy Fuels 28 (2014) 5872-5881;

(b) M.-J. Jin, A. Taher, H.-J. Kang, M. Choi, R. Ryoo, Green Chem. 11 (2009) 309-313;

(c) F. Li, Q. Zhang, Y. wang, Appl. Catal. A: Gen. 334 (2008) 217-226.

[16] (a) Z. Chen, P. Zou, R. Zhang, L. Dai, Y. Wang, Catal. Lett. 145 (2015) 2029-2036;

(b) A. Fooder, Z. Hell, L. Pirault-Roy, Appl. Catal. A: Gen. 484 (2014) 39-50;

(c) Y. Chen, Z. Guo, T. Chen, Y. Yang, J. Catal. 275 (2010) 11-24;

(d) T. Maegawa, T. Takahashi, M. Yoshimura, H. Suzuka, Y. Mongchuhi, H. Sagiki, Adv. Synth. Catal. 351 (2009) 2091-2095.

[17] (a) R.N. d'Alnoncourt, M. Friedrich, E. Kunkes, D. Rosenthal, F. Girgsdies, B. Zhang, L. Shao, M. Schuster, M. Behrens, R. Schlögl, J. Catal. 317 (2014) 220-228;

(b) K. Okumura, T. Kobayashi, H. Tanaka, M. Niwa, Appl. Catal. B: Environmental 44 (2003) 325-331.

[18] V. Andrushko, D. Schwinn, C.C. Tzschucke, F. Michalek, J. Hörn, C. Mossner, W. Bannwarth, Helv. Chim. Acta 88 (2005) 936–949.

[19] (a) Y. He, C. Cai, Catal. Commun. 12 (2011) 678-683;
(b) S.M. Islam, P. Mondal, K. Tuhina, A.S. Roy, S. Mondal, D. Hossain, J. Inorg. Organomet. Polym. 10 (2010) 264-277;
(c) Y. He, C. Cai, Appl. Organomet. Chem. 25 (2011) 799-803.

[20] (a) I. Davidi, D. Patra, D. Hermida-Merino, G. Portale, V.M. Rotello, U. Raviv, R. Shenhar, Macromolecules 47 (2014) 5774-5783;
(b) K. Yu, W. Sommer, M. Weck, C.W. Jones, J. Catal. 226 (2004) 101-110.

[21] (a) Y. Huang, L. Yang, M. Huang, J. Wang, L. Xu, W. Li, H. Zhou, X. Sun, H. Xing, H. Liu, Particuology 22 (2015) 128-133;
(b) X.-Q. Yu , J.-S. Huang , W.-Y. Yu , C.M. Che, J. Am. Chem. Soc. 122 (2000) 5337-5342.

[22] F. Glorius, in: F. Glorius (Ed.), N-Heterocyclic Carbenes in Transition Metal Catalysis, Springer, Berlin, 2007.

[23] (a) A.J. Arduengo, R.L. Harlow, M. Kline, Journal of the American Chemical Society 113 (1991) 361–363;
(b) C.S.J. Cazin, Comptes Rendus Chimie 12 (2009) 1173–1180.

[24] (a) W.A. Herrmann, Angew. Chem., Int. Ed. 41 (2002) 1290-1309;
(b) A.A. Danopoulos, D. Pugh, H. Smith, J. Sassmannshausen, Chem. Eur. J. 15 (2009) 5491-5502;
(c) K.H. Shaughnessy, Chem. Rev. 109 (2009) 643-710;
(d) C.S. J. Cazin (Ed.), N-Heterocyclic Carbenes in Transition Metal Catalysis and Organocatalysis, Springer, Netherlands, 2011;
(e) S. Diez-Gonzalez, N. Marion, S.P. Nolan, Chem. Rev. 109 (2009) 3612–3676;
(f) F.E. Hahn, M.C. Jahnke, Angew. Chem., Int. Ed., 47 (2008) 3122–3172.

[25] (a) T. Weskamp, F.J. Kohl, W. Hieringer, D. Gleich, W.A. Herrmann, Angew. Chem., Int. Ed. 38 (1999) 2416–2419;
(b) J. Schwarz, V.P.W. Böhm, M.G. Gardiner, M. Grosche, W.A. Herrmann, W. Hieringer, G. Raudaschl-Sieber, Chem. Eur. J. 6 (2000) 1773–1780.

[26] (a) S. Xu, K. Song, T. Li, B. Tan, J. Mater. Chem. A 3 (2015) 1272-1278;
(b) D.-H. Lee, J.-H. Kim, B.-H. Jun, H. Kang, J. Park, Y.-S. Lee, Org. Lett. 10 (2008) 1609-1612;
(c) T. Kang, Q. Feng, M. Luo, Synlett (2005) 2305-2308;
(d) M. Shokouhimehr, J.-H. Kim, Y.-S. Lee, Synlett (2006) 618-620.
(e) J.-W. Byun, Y.-S. Lee, Tetrahedron Lett. 45 (2004) 1837-1840.

[27] D.B. Bagal, R.A. Watile, M.V. Khedkar, K.P. Dhake, B.M. Bhanage, Catal. Sci. Technol. 2 (2012) 354-358.

[28] Z.S. Qureshi, S.A. Revankar, M.V. Khedkar, B.M. Bhanage, Catal. Today 198 (2012) 148-153.

[29] F.-T. Luo, H.-K, Lo, J. Organomet. Chem. 696 (2011) 1262-1265.

[30] (a) B. Movassagh. A. Takallou, A. Mobaraki, J. Mol. Catal. A: Chem. 401 (2015) 55-65;
(b) B. Movassagh, N. Rezaei, Tetrahedron 70 (2014) 8885-8892.

[31] M.A. Iqbal, R.A. Haque, S.F. Nasri, A.M.S.A. Majid, M.B.K. Ahamed, E. Farsi, T. Fatima, Chem. Cent. J. 7 (2013) 27.

[32] M.A. Iqbal, R.A. Haque, M.B.K. Ahamed, A.M.S.A. Majid, Biochem. Anal. Biochem. 3 (2014) 1-6.

[33] F. Galindo, B. Altava, M.I. Burguete, R. Gavara, S.V. Luis, J. Combinatorial Chem. 6 (2004) 859-861.

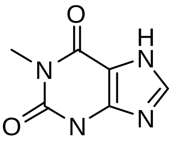
[34] (a) G, Buscemi, M. Basato, A. Biffis, A. Gennaro, A.A. Isse, M.M. Natile, C. Tubaro, J. Organomet. Chem. 695 (2010) 2359-2365;
(b) Y. Xu, L. Zhang, Y. Cui, J. Appl. Polym. Sci. 110 (2008) 2996-3000.

[35] H. Yang, X. Han, G. Li, Y. Wang, Green Chem. 11 (2009) 1184-1193.

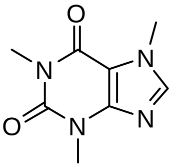
[36] (a) E. Melnik, P. Muellner, O. Bethge, E. Bertagnolli, R. Hainberger, M. Laemmerhofer, Chem. Commu. 50 (2014) 2424-2427;
(b) X. Wang, P. Hu, F. Xue, Y. Wei, Carbohydr. Polym. 114 (2014) 476-483;
(c) Y.-L. Huang, H.-W. Tien, C.-C.M. Ma, S.-Y. Yang, S.-Y. Wu, H.-Y. Liu, Y.-W. Mai, J. Mater. Chem. 21 (2011) 18236-18241.

[37] (a) Z. Li, J. Liu, Z. Huang, Y. Yang, C. Xia, F. Li, ACS Catal. 3 (2013) 839-845;
(b) S. Souto, M. Pickholz, M.C. dos Santos, F. Alvarez, Phys. Rev. B 57 (1998) 2536-2540.

[38] J.G. Taylor, A.V. Moro, C.R.D. Correia, Eur. J. Org. Chem. 2011 (2011) 1403-1428.



theophylline



caffeine

Figure 1. Xanthine derivatives.

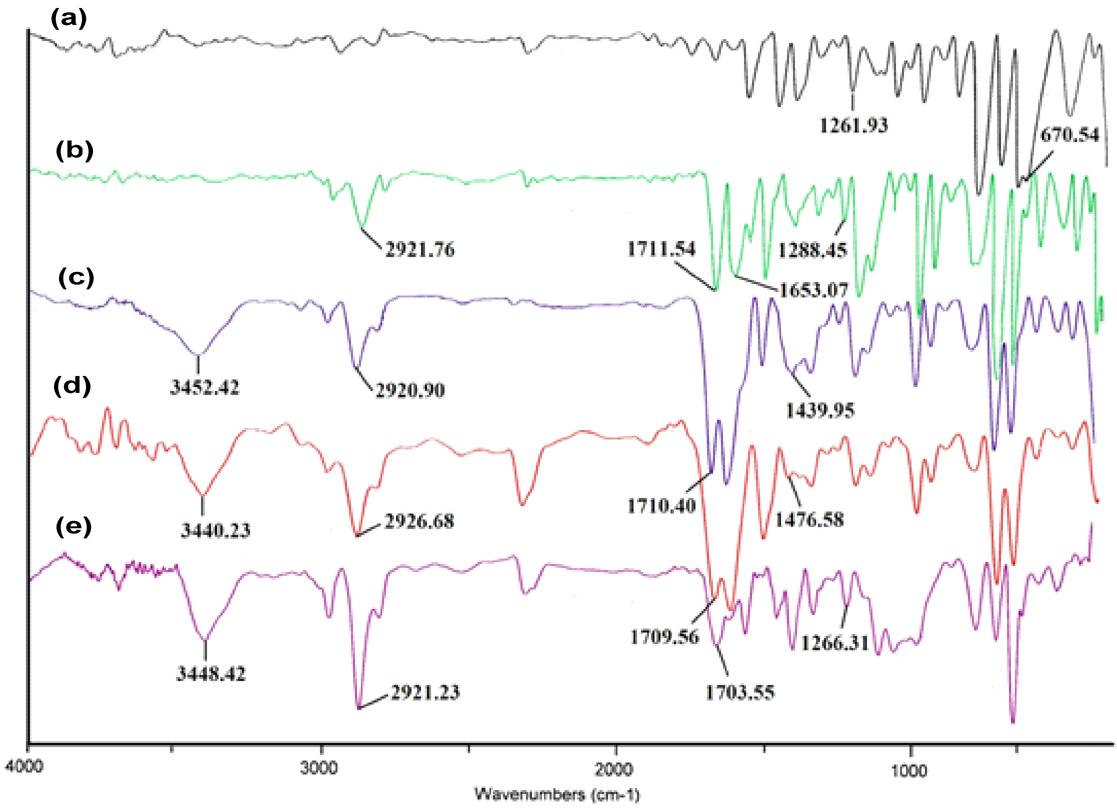


Figure 2. IR spectra of chloromethylated polystyrene resin (a), polystyrene-supported theophylline (b), polystyrene-supported IL (c), polystyrene-supported Pd(II)-NHC complex (d), and polystyrene-supported caffeine (e).

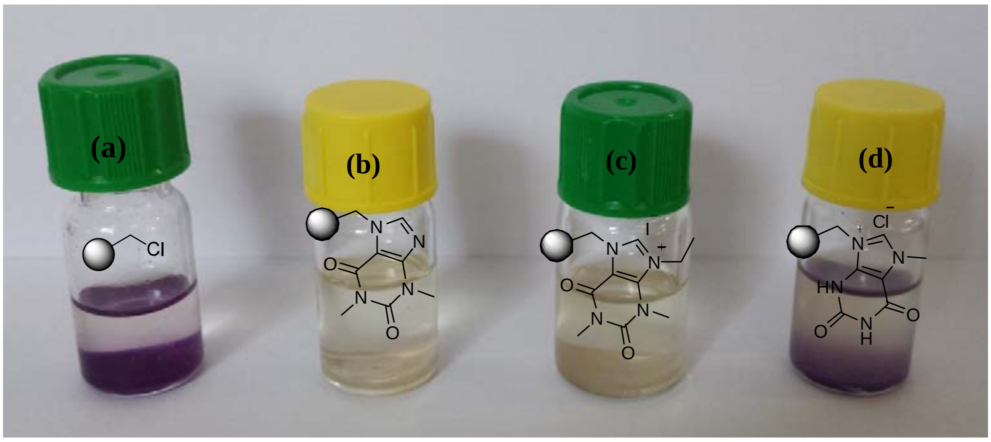


Figure 3. The NBP test result for the chloromethylated polystyrene resin (a), polystyrene-supported theophylline (b), polystyrene-supported IL (c), and polystyrene supported caffeine (d).

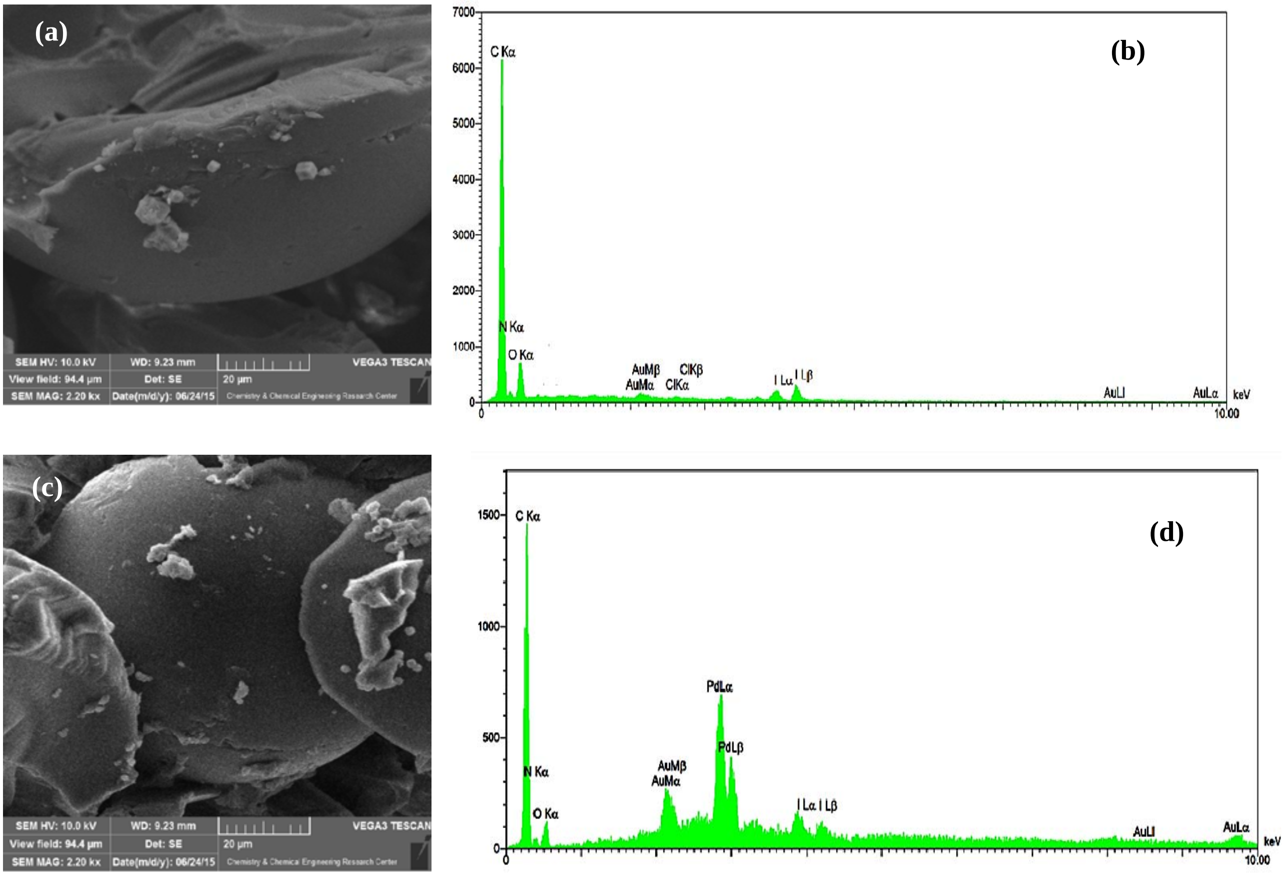


Figure 4. SEM images of polystyrene-supported IL **2** (a), and polystyrene-supported Pd(II)-NHC (**3**) complex (c) and EDX data of PS-IL **2** (b), and PS-NHC-Pd(II) (**3**) (d).

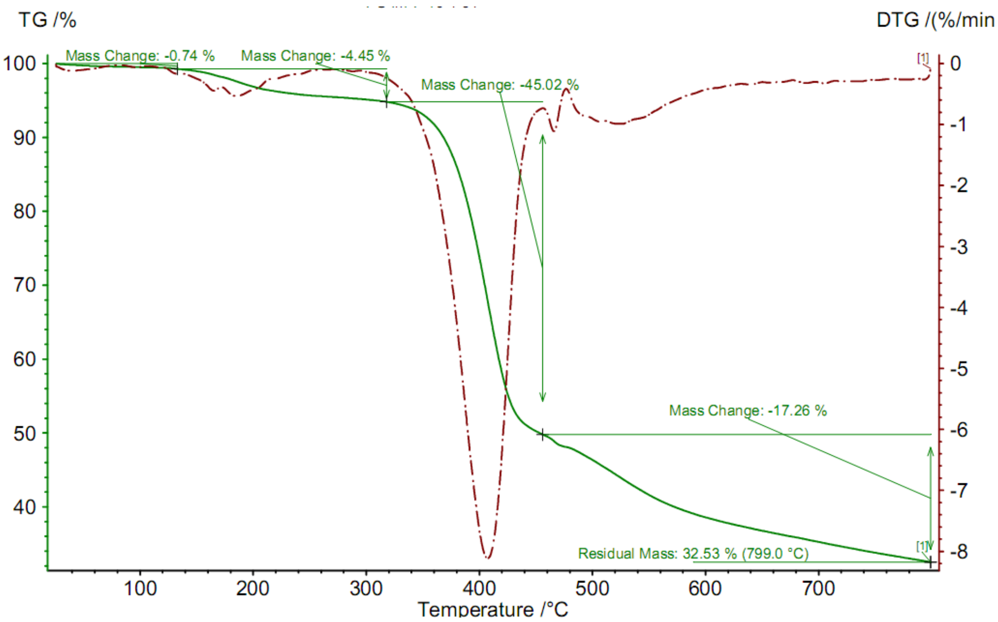


Figure 5. Thermogravimetric weight loss plot for the PS-NHC-Pd(II) (**3**) catalyst.

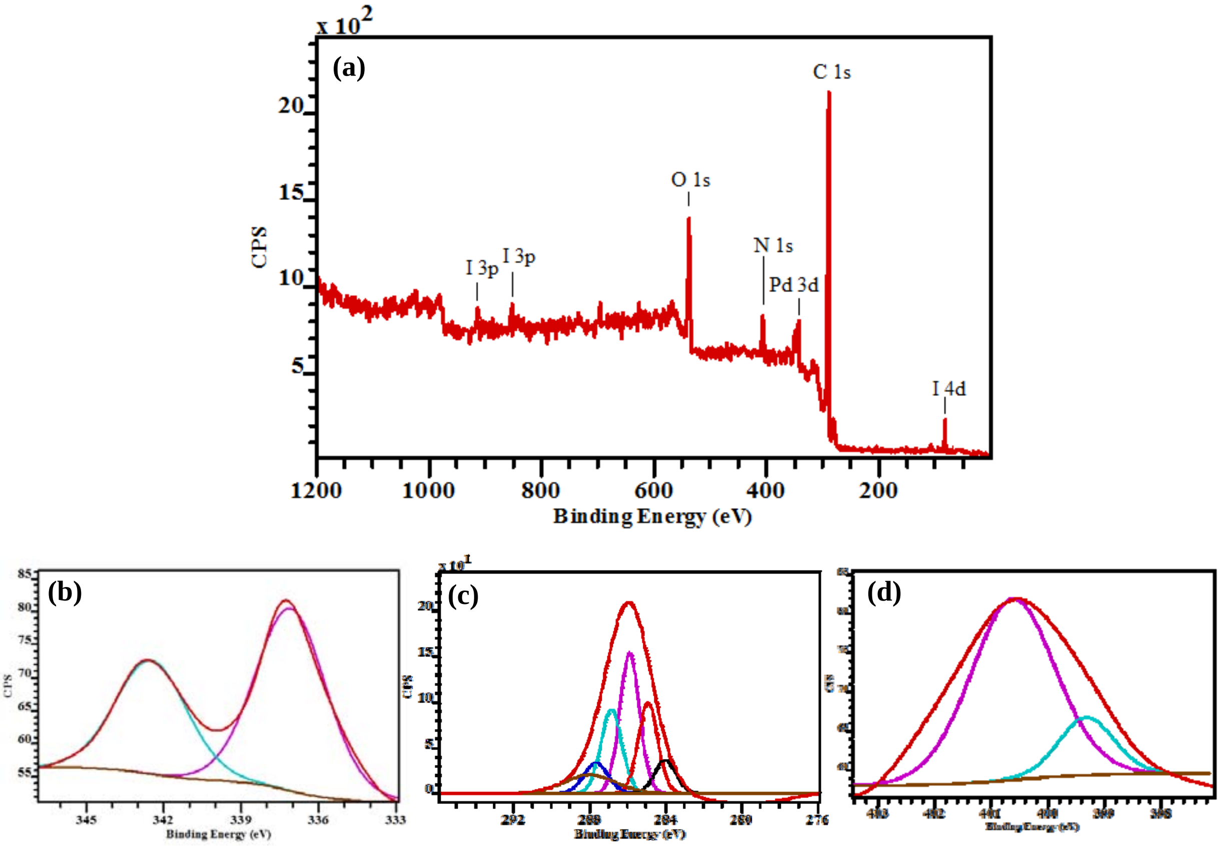


Figure 6. Full range XPS spectrum (a), the Pd 3d (b), C 1s (c), and N 1s (d) of PS-NHC-Pd(II) (**3**), respectively.

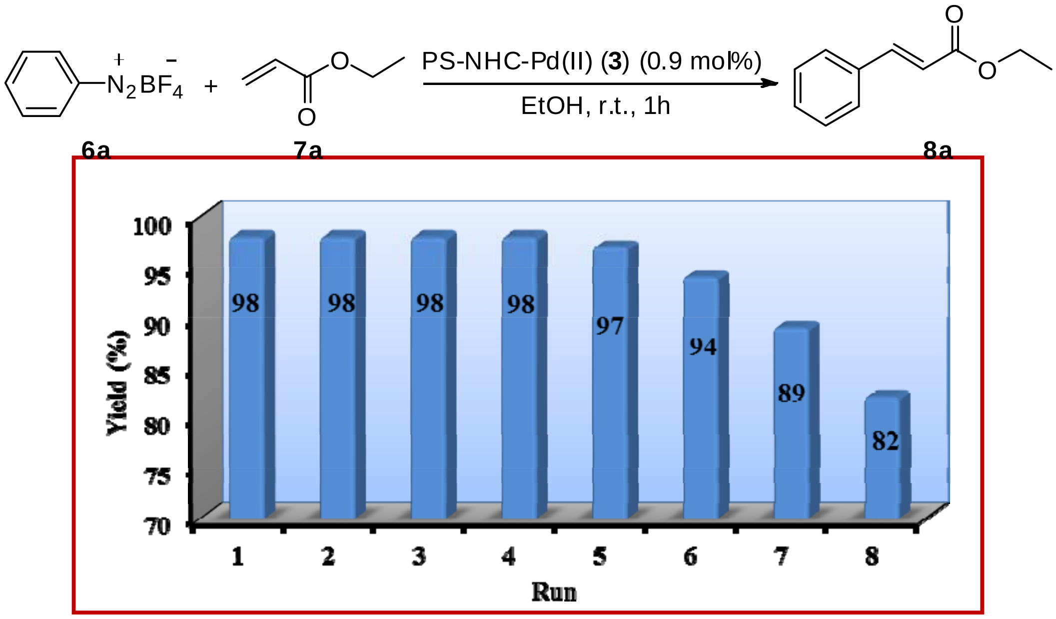
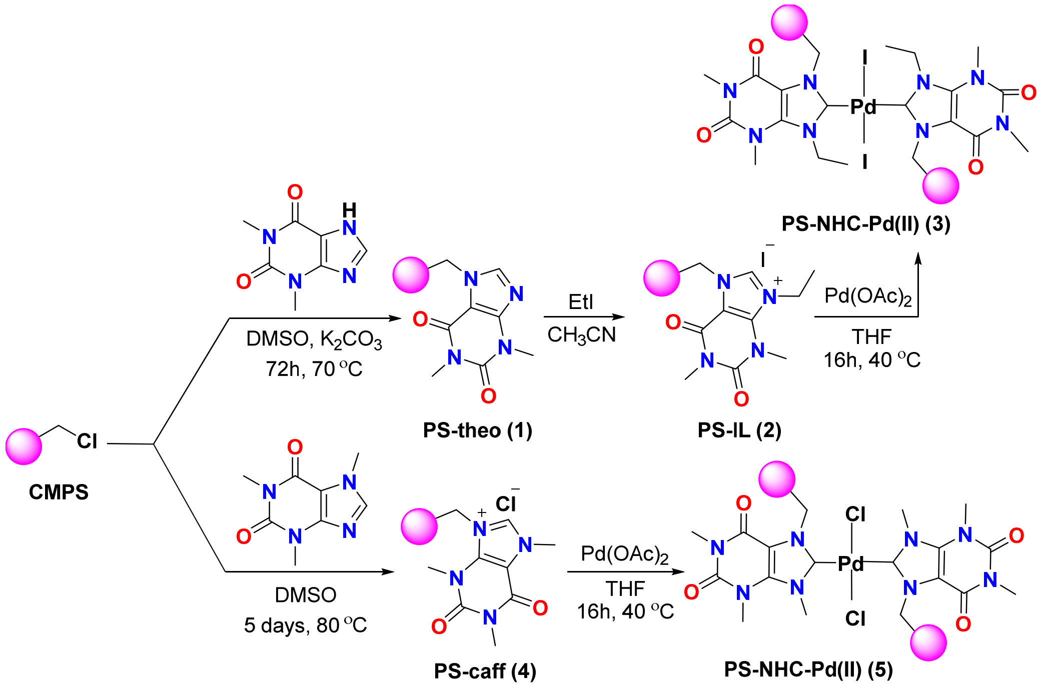
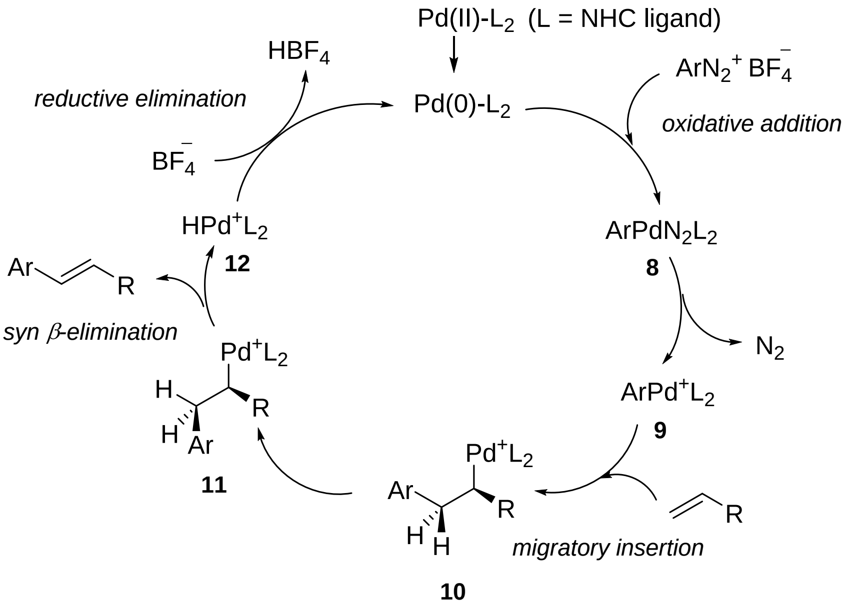


Figure 7. Recycling activity of the PS-NHC-Pd(II) (**3**) catalyst; reaction conditions: benzenediazonium tetrafluoroborate salt (0.5 mmol), ethyl acrylate (0.75 mmol), PS-NHC-Pd(II) (**3**) (0.9 mol%), in EtOH (1 mL), at room temperature.



Scheme 1. Synthesis of functionalized supported NHC ligands and palladium(II)-NHC complexes.

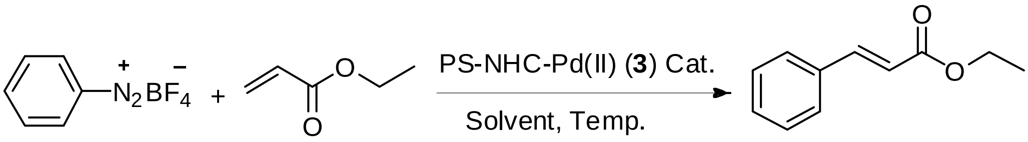


Scheme 2. Plausible mechanism for the Heck-Matsuda cross-coupling reaction.

Table 1. Chemical composition of various PS supported compounds.

Entry	Compound	C %	H %	N %	Pd %
1	PS-theo (**1**)	65.70	6.0	15.41	-
2	PS-IL (**2**)	64.50	5.37	13.94	-
3	PS-NHC-Pd(II) (**3**)	68.04	5.97	12.34	3.31
4	PS-caff (**4**)	71.35	6.91	4.21	-
5	PS-NHC-Pd(II) (**5**)	72.96	6.65	5.32	1.1

Table 2. Optimization of the reaction conditions for Heck-Matsuda cross-coupling reaction.[a]

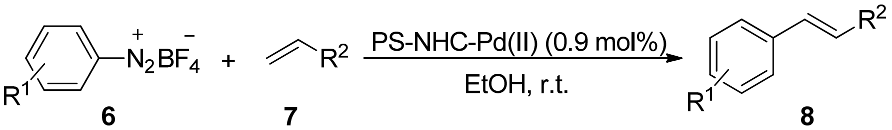


6a **7a** **8a**

Entry	Solvent (ratio)	Catalyst (mol% of Pd)	Temp. (ºC)	Time (h)	Yield[b] (%)
1	THF	0.9	25	1	15
2	CH_3CN	0.9	25	1	26
3	MeOH	0.9	25	1	72
4	EtOH	0.9	25	1	98
5	H_2O	0.9	25	24	trace
6	EtOH:H_2O (1:1)	0.9	25	24	57
7	EtOH	1.1	25	1	98
8	EtOH	0.7	25	1	84
9	EtOH	0.9	40	1	98
10	THF	0.9	25	24	33[c]

[a] Reaction conditions: arenediazonium tetrafluoroborate salt (0.5 mmol), olefin (0.75 mmol), and catalyst (**3**) in solvent (1 mL) at room temperature. [b] Isolated yields. [c] Benezendiazonium tetrafluoroborate (**6a**) was generated *in situ* using aniline, $BF_3.OEt_2$ and ^{t}BuONO.

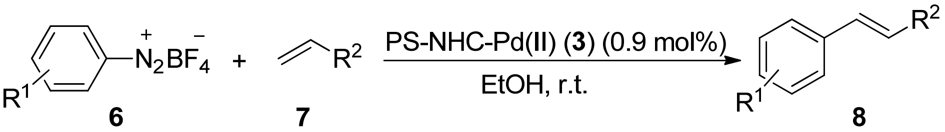
Table 3. Comparison of catalytic activity of PS-NHC-Pd(II) (**3**) and (**5**)[a]



Entry	R¹	R²	Catalyst **3**		Catalyst **5**	
			Time (h)	Yield[b] (%)	Time (h)	Yield[b] (%)
1	H	CO_2Et	1	98, 98[c]	2.5	80, 59[c]
2	4-MeO	CO_2Et	2.5	92	4	72
3	4-NO_2	CO_2Et	0.67	97	1.5	84

[a] Reaction conditions: arenediazonium tetrafluoroborate salt (0.5 mmol), olefin (0.75 mmol), and PS-NHC-Pd(II) catalyst (0.9 mol%) in EtOH (1 mL) at room temperature. [b] Isolated yields. [c] Yield of the 2nd cycle.

Table 4. Heck-Matsuda arylation of the olefins with arenediazonium salts[a]



Entry	R¹	R²	product	Time (h)	Yield[b] (%)
1	H	CO_2Et	**8a**	1	98
2	4-Me	CO_2Et	**8b**	1	96
3	3-Me	CO_2Et	**8c**	1	95
4	2-Me	CO_2Et	**8d**	1	93
5	4-MeO	CO_2Et	**8e**	2.5	92
6	4-NO_2	CO_2Et	**8f**	0.66	97
7	4-I	CO_2Et	**8g**	2	91
8	4-Me	CO_2Me	**8h**	1	95
9	4-MeO	CO_2Me	**8i**	2.25	93
10	4-Br	CO_2Me	**8j**	2	93

11	4-Me	$CO_2{}^{n}Bu$	**8k**	1	94
12	H	$CONH_2$	**8l**	1	86
13	4-NO_2	$CONH_2$	**8m**	0.75	93
14	2-Me	$CONH_2$	**8n**	3	78
15	H	Ph	**8o**	8	51
16	4-NO_2	Ph	**8p**	4	82
17	4-Cl	Ph	**8q**	4	71
18	H	4-ClC_6H_4	**8r**	6	66
19	4-NO_2	4-$MeOC_6H_4$	**8s**	4	88

[a] Reaction conditions: arenediazonium tetrafluoroborate salt (0.5 mmol), olefin (0.75 mmol), PS-NHC-Pd(II) (**3**) catalyst (0.9 mol%), in EtOH (1 mL), at room temperature. [b] Isolated yields; all products were analyzed by NMR technique.