J IRAN CHEM SOC
DOI 10.1007/s13738-013-0271-z

ORIGINAL PAPER

Immobilized palladium nanoparticles on silica functionalized *N*-propylpiperazine sodium *N*-propionate (SBPPSP): catalytic activity evaluation in copper-free Sonogashira reaction

**Khodabakhsh Niknam · Abdollah Deris ·
Farhad Panahi · M. Reza Hormozi Nezhad**

Received: 6 January 2013 / Accepted: 9 May 2013

Abstract An efficient heterogeneous palladium catalyst system has been developed based on immobilization of Pd nanoparticles on silica-bonded *N*-propylpiperazine sodium *N*-propionate (SBPPSP) substrate. SBPPSP substrate can stabilize the Pd nanoparticles effectively so that it can improve their stability against aggregation. In addition, grafted piperazine species on to the silica backbone prevent the removing of Pd nanoparticles from the substrate surface. Transmission electron microscopy (TEM) of catalyst is shown the size of Pd nanoparticles, also it confirmed by particle size analyzer which shown the average size of 21 nm for Pd. The catalytic activity of these catalysts was investigated in the Sonogashira reaction. The catalyst could be recycled several times without appreciable loss in catalytic activity.

Keywords Heterogeneous palladium nanoparticles · Silica-bonded *N*-propylpiperazine sodium *N*-propionate · Sonogashira reaction · Aryl halides · Alkynes

Introduction

The most frequently utilized method for the preparation of alkynylarenes is the Sonogashira–Hagihara reaction, in which C(aryl)–C(sp) bonds are constructed by the palladium/copper-catalyzed cross-coupling of aryl halides and terminal alkynes [1–4]. Since its discovery by Sonogashira and co-workers in 1975, considerable research has been devoted to the synthetic application of the reaction as well as to improve its efficiency [1]. One of the major problems associated with it lies in the reaction conditions where the use of both a palladium catalyst and a copper reagent (co-catalyst) is frequently required to promote the reaction, resulting in contamination of the coupling products with metal residue. In addition, it has been well-documented that the Sonogashira coupling often suffers from the Glaser-type oxidative dimerization of the alkyne substrate [5], as a side reaction in the presence of a Cu(I) co-catalyst. Recently, quite a few reports addressing these problems have appeared, in which the coupling is carried out with an immobilized palladium catalyst and/or under copper-free conditions [6–10].

In the recent years, there is considerable attention on preparation of heterogeneous palladium catalyst based on the nanometer scale palladium species [11–14]. Palladium nanoparticles on a suitable support have the ability to be recoverable and ligand-free catalytic systems with improved catalyst characteristics [11–24]. Usually, palladium nanoparticle catalysts are prepared from a palladium salt, on a substrate or stabilizer in the presence of a reducing agent [14–27]. Steric, electrostatic, and electrosteric factors are responsible for the stabilization of Pd nanoparticles during their synthesis.

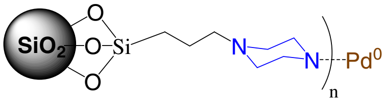
Recently, we introduced Pd nanoparticles on silica-bonded *N*-propylpiperazine (PNP-SBNPP) as an efficient catalyst for Heck and Suzuki reactions (Scheme 1) [14].

Electronic supplementary material The online version of this article (doi:10.1007/s13738-013-0271-z) contains supplementary material, which is available to authorized users.

K. Niknam (✉) · A. Deris · F. Panahi
Department of Chemistry, Faculty of Sciences,
Persian Gulf University, Bushehr 75169, Iran
e-mail: niknam@pgu.ac.ir

M. Reza Hormozi Nezhad
Department of Chemistry, Sharif University of Technology,
Tehran 11155-9516, Iran

M. Reza Hormozi Nezhad
Institute for Nanoscience and Nanotechnology (INST),
Sharif University of Technology, Tehran 9161, Iran



Scheme 1 The synthetic rout for preparation of PNP-SBNPP

Herein, we describe the preparation of immobilized palladium nanoparticles on silica-bonded *N*-propylpiperazine sodium *N*-propionate (PNP-SBPPSP) as catalyst and the catalytic activity of both PNP-SBPPSP and PNP-SBNPP is investigated in the Sonogashira cross-coupling reactions.

Experimental

Chemicals and reagents

Chemicals were purchased from Fluka, Merck and Aldrich Chemical Companies. The products were characterized by comparison of their spectral and physical data with those reported in literature [7–11]. For recorded ^{1}H-NMR spectra, we were using Bruker Avance (DRX 500 MHz) in pure deuterated $CDCl_3$ solvent with tetramethylsilane (TMS) as internal standards. X-ray diffraction (XRD, D8, Advance, Bruker, axs), FT-IR spectroscopy (Shimadzu FT-IR 8000 spectrophotometer), and SEM instrumentation (SEM, XL-30 FEG SEM, Philips, at 20 kV) were employed for characterization of catalyst. Melting points determined in open capillary tubes in a Barnstead Electrothermal 9100 BZ circulating oil melting point apparatus. The reaction monitoring was accomplished by TLC on silica gel PolyGram SILG/UV254 plates. Column chromatography was carried out on columns of silica gel 60 (70–230 mesh). Silica-bonded *N*-propylpiperazine (SBNPP) and Pd nanoparticles on silica-bonded *N*-propylpiperazine (PNP-SBNPP) were prepared according to our reported procedure [14, 28].

Preparation of silica-bonded N-propylpiperazine methyl N-propionate (SBPPMP)

To a magnetically stirred mixture of SBNPP (25 g) in MeOH (50 mL), methyl acrylate (25 mL) was added and heated at 40–50 °C for 48 h under nitrogen [29]. Then, the mixture was filtered and washed with methanol (2 × 50 mL) and dried 8 h under vacuum to afford silica-bonded *N*-propylpiperazine methyl *N*-propionate (SBPPMP) as a white powder (26.6 g). Elemental analysis gave the results: C, H, and N content to be 13.47, 2.28, and 2.18 %, respectively.

Preparation of silica-bonded N-propylpiperazine sodium N-propionate (SBPPSP)

To a magnetically stirred mixture of (SBPPMP) (26.6 g) was treated with HCl (0.5 M, 50 mL), and then the mixture was filtered and dried overnight under vacuum [29]. Subsequently, the mixture was treated with saturated solution of $NaHCO_3$ (50 mL) over 2 h. Then, the mixture was filtered and dried overnight under vacuum to afford silica-bonded *N*-propylpiperazine sodium *N*-propionate (SBPPSP) as a white powder (26.7 g). Elemental analysis gave the results: C, H, and N content to be 13.72, 2.30, and 2.78 %, respectively. The C/N relationship observed and calculated is 4.93 and 4.28, respectively.

Preparation of Pd nanoparticles on silica-bonded N-propylpiperazine sodium N-propionate (PNP-SBPPSP)

To a mixture of (SBPPSP) (1 g) in absolute ethanol (10 mL), palladium acetate (0.15 g, 0.67 mmol) was added and stirred 24 h at room temperature. Then, the mixture was filtered and washed with ethanol (3 × 10 mL). After drying in vacuum oven Pd nanoparticles on silica-bonded *N*-propylpiperazine sodium *N*-propionate (PNP-SBPPSP) was obtained as dark solid (1.1 g).

General procedure for Sonogashira cross-coupling reaction

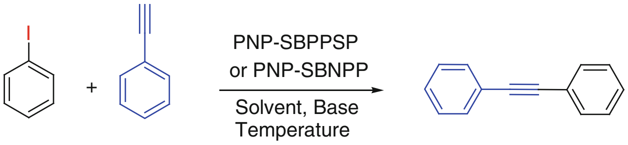
A mixture of aryl halide (1 mmol), alkyne (1.2 mmol), triethylamine (4 mmol), PNP-SBPPSP (0.05 g, 2.6 mol %) [or PNP-SBNPP (0.05 g, 2.8 mol %)], and acetonitrile (3 mL) was stirred under reflux conditions for the time specified in Table 2. The reaction was followed by TLC. After completion of the reaction, the mixture was cooled down to room temperature and filtered, and the remaining was washed with dichloromethane (3 × 10 mL) to separate catalyst. After extraction dichloromethane from water, the organic phase dried over Na_2SO_4. Evaporation of the solvent gave products. For further purification if needed, the products passed through a short column of silica gel using n-hexane as eluent.

Selected NMR data: 2-methyl-phenylethynyl-benzene (Table 1, entry 10): ^{1}H-NMR (500 MHz, $CDCl_3$): δ (ppm) 2.56 (s, 3H, CH_3), 7.19–7.22 (m, 1H, Ar), 7.26–7.28 (m, 2H, Ar), 7.36–7.41 (m, 3H, Ar), 7.54 (d, 1H, $J = 7.5$ Hz, Ar), 7.56–7.58 (m, 2H, Ar). ^{13}C-NMR (125 MHz, $CDCl_3$): δ (ppm) 21.17, 94.01, 98.51, 124.10, 126.00, 128.59, 128.72, 128.77, 129.88, 131.93, 132.26, 140.81.

The recyclability of PNP-SBPPSP as catalyst in the reaction of iodobenzene and phenylacetylene

A mixture of iodobenzene (2 mmol, 0.408 g), phenylacetylene (2.4 mmol, 0.245 g), triethylamine (8 mmol), PNP-SBPPSP (0.1 g), and acetonitrile (5 mL) was stirred under reflux conditions. The reaction was followed by TLC. After completion of the reaction (1.0 h), the mixture was cooled

Table 1 Optimization reaction between iodobenzene and phenylacetylene in the presence of PNP-SBPPSP as a catalyst at various conditions



Entry	Solvent	Base	Catalyst loading (g)	Temp/°C	Time/h	Yield^{a,b} * (%)
1	DMF	Na_2CO_3	0.075	120	1.5 (1.5)	85 (83)
2	H_2O	Na_2CO_3	0.075	Reflux	1.0 (1.0)	25 (28)
3	H_2O	Cs_2CO_3	0.075	Reflux	1.0 (1.0)	25 (26)
4	CH_3CN	Na_2CO_3	0.075	Reflux	2.0 (2.0)	66 (67)
5	CH_3CN	Et_3N	0.075	Reflux	1.0 (1.0)	92 (92)
6	CH_3CN	Et_3N	0.05	Reflux	1.5 (1.5)	87 (86)
7	CH_3CN	Et_3N	0.03	Reflux	12 (12)	60 (60)
8	CH_3CN	Et_3N	0.01	Reflux	12 (12)	32 (30)
9	CH_3CN	Et_3N	0.1	Reflux	1.0 (1.0)	93 (92)

Reaction conditions: iodobenzene (1 mmol), phenylacetylene (1.2 mmol) and base (4 mmol) in solvent (3 mL)

[a] Isolated yield

[b] The times and yields in parenthesis related to PNP-SBNPP

down to room temperature and filtered, and the remaining was washed with dichloromethane (3 × 10 mL) to separate catalyst. After extraction dichloromethane from water, the organic phase dried over Na_2SO_4. Evaporation of the solvent gave product which passed through a short column of silica gel using n-hexane as eluent (0.327 g of product 92 %). The recycled catalyst was used in next run.

Results and discussion

Catalyst preparation and characterization

As shown in Scheme 2, immobilized palladium nanoparticles on piperazine-modified silica (Pd-SBPPSP) are prepared in a four-step process. First, activated silica was reacted with 3-chloropropyl trimethoxysilane in refluxing toluene to produce 3-chloropropylsilica (3-CPS) [21]. Second, 3-CPS was treated with piperazine to generate the silica-bonded *N*-propylpiperazine substrate [14, 28, 29]. Third, silica-bonded *N*-propylpiperazine treated with methylacrylate and followed by hydrolysis to obtain silica-bonded *N*-propylpiperazine sodium *N*-propionate (SBPPSP) [29]. Finally, palladium acetate is reduced on SBPPSP substrate using ethanol as green reducing agent [22]. The Pd species stabilized by grafted ligand through the amine and carboxylate groups (Scheme 2) [27, 30].

TEM image of PNP-SBPPSP catalyst (Fig. 1) shows that the Pd nanoparticles with near spherical morphology are assembled on to the silica bonded *N*-propylpiperazine sodium *N*-propionate support with a relatively good monodispersity.

In addition, the histogram revealing the size distributions of Pd nanoparticles on SBPPSP substrate is shown in Fig. 2 and is proposed according to the data obtained from the TEM image. The average sizes of Pd nanoparticles for Pd-SBPPSP catalyst are obtained 21 nm.

The microscopic features of the catalyst were observed with SEM (Fig. 3). In this figure, we can see morphology of the silica substrate.

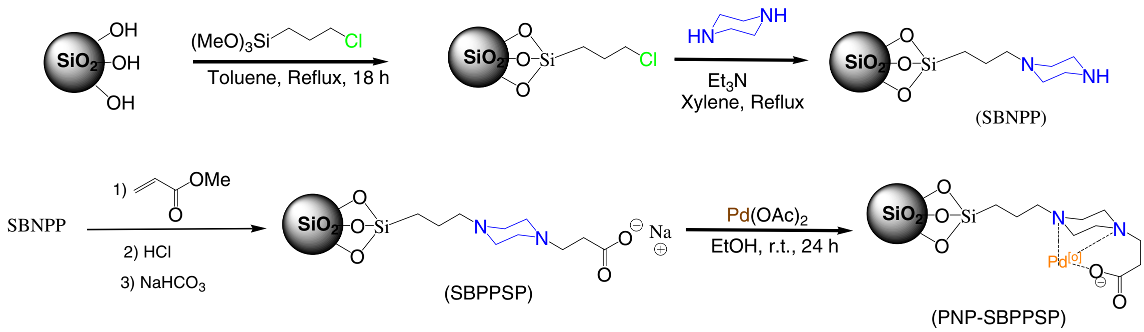
The crystalline structure of the PNP-SBNPP catalyst is displayed by the XRD pattern depicted in Fig. 4. The XRD pattern of the PNP-SBNPP catalyst also shows palladium nanoparticles on the silica surface. The strongest peaks of the XRD pattern correspond to SiO_2, and other peaks are indexed as the (111), (200), (220), and (311) planes of the palladium nanoparticle [14, 21].

The BET surface area using nitrogen adsorption isotherms at the temperature of liquid nitrogen which gave the results of $a_{s,BET}$ 1.40 $m^2\ g^{-1}$ and the total pore volume 0.2505 $cm^3\ g^{-1}$ (see supplementary material).

To confirm the Pd content, the supported catalyst was treated with concentrated HCl and HNO_3 to digest the Pd species and then analyzed by ICP analysis. The Pd content for PNP-SBPPSP was determined to be 55.6 ppm (55.6 mg L^{-1} = 5.56 % w/w).

After characterization of catalyst, its catalytic activity is tested in Sonogashira cross-coupling reactions.

We tested various conditions to optimize the amount of PNP-SBPPSP and PNP-SBNPP catalysts on the Sonogashira reaction between iodobenzene and phenylacetylene (Table 1). The optimized amount of PNP-SBPPSP catalyst was 0.05 g (2.6 mol % of Pd) [or PNP-SBNPP catalyst 0.05 g (2.8 mol %)].



Scheme 2 The synthetic route for preparation of PNP-SBPPSP

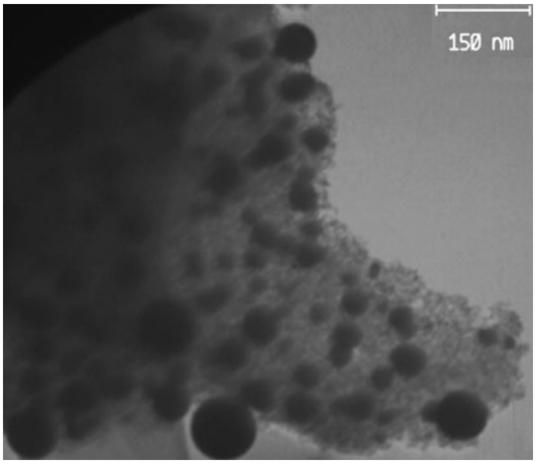


Fig. 1 Transmission electron microscope (TEM), which show the image of Pd nanoparticle on SBPPSP support

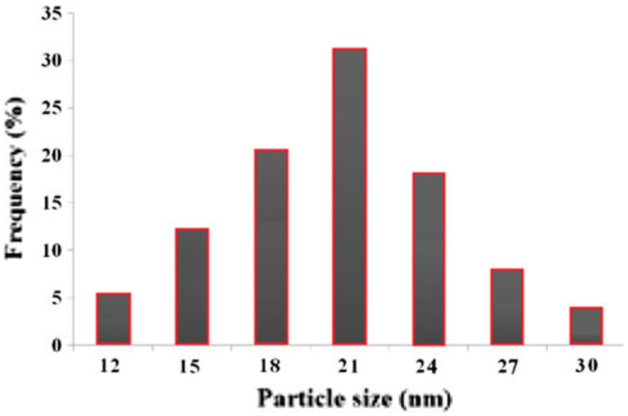


Fig. 2 Histogram representing the size distribution of Pd nanoparticles on SBPPSP substrate

By decreasing the catalyst to 0.01 g (0.52 mol % of Pd) [or PNP-SBNPP catalyst 0.01 g (0.56 mol %)], the yield of product decreased and the time of reaction was increased (Table 1, entry 8), while the increase of catalyst to 0.1 g (5.2 mol % of Pd) [or PNP-SBNPP catalyst 0.1 g (5.6 mol %)] did not have more effect on the reaction yield (Table 1, entry 9). In addition, different conditions, such as solvent, base and temperature were optimized and the result was shown in Table 1. The optimized conditions was aryl halide (1 mmol), phenylacetylene (1.2 mmol), triethylamine (4 mmol), and PNP-SBPPSP (0.05 g, 2.6 mol %) [or PNP-SBNPP catalyst 0.05 g (2.8 mol %)] in 3 mL acetonitrile as solvent under reflux conditions.

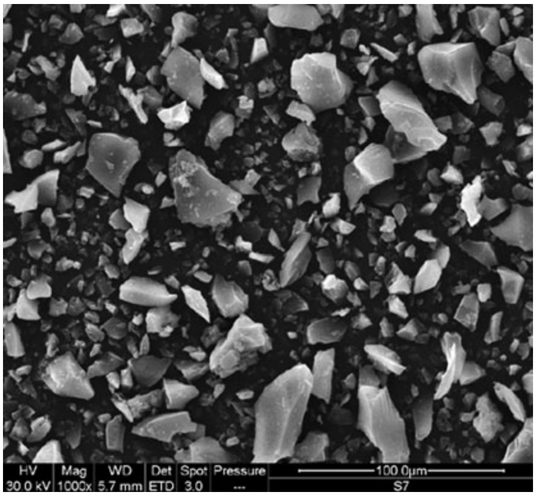
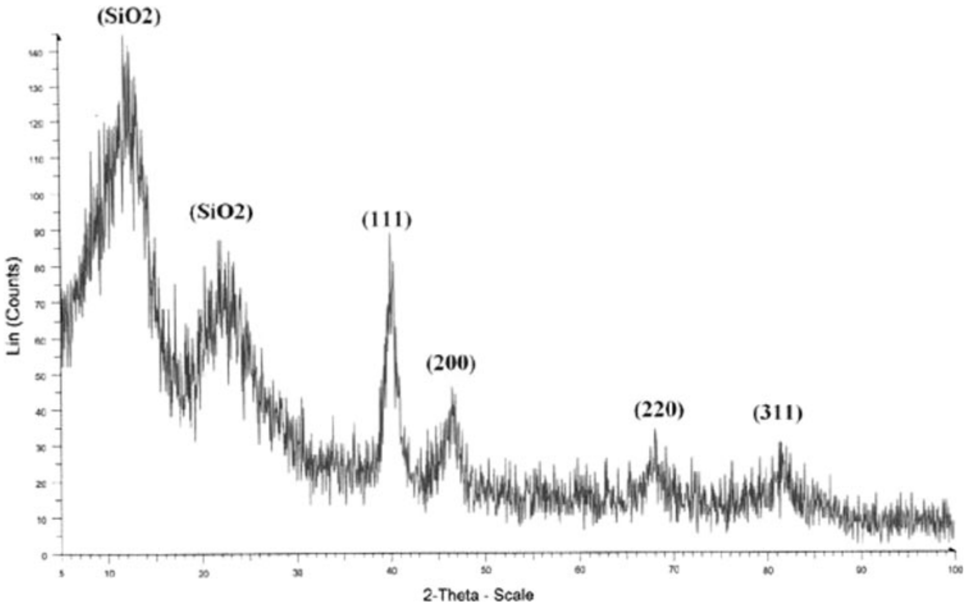


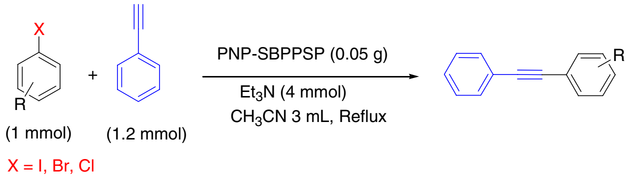
Fig. 3 SEM of PNP-SBPPSP

The generality of this protocol was applied for coupling of various alkynes with aryl halides (Scheme 3; Table 2).

Phenylacetylene was found to couple smoothly with iodobenzene providing good yield (87 %) of the desired product (Table 1, entry 6). In addition, phenylacetylene was coupled with bromobenzene and chlorobenzene in 85 and 45 % yield, respectively (Table 2, entries 2–5). Functional groups like methoxy, methyl, and nitro were well tolerated under the present catalytic system (Table 2, entries 6–10). The electron-donating groups on the aryl ring decreased the reaction rate and also yield of product (Table 2, entries 8–10). Sterically hindered 2-iodo toluene was treated with phenylacetylene under optimized conditions providing 82 % yield of the desired product (Table 2, entry 10). The electron-withdrawing groups on the aryl ring increased the reaction rate and also yield of product

Fig. 4 XRD of PNP-SBPPSP





Scheme 3 PNP-SBPPSP catalyzed couper-free Sonogashira cross-coupling reactions

Table 2 The react ion of phenylacetylene with aryl halides in the presence of PNP-SBPPSP as catalyst (Sonogashira reaction)

Entry	Aryl halide	Catalyst loading (g)	Time/h	Yield^{a,b} (%)
1	C_6H_5-I	0.075	1 (1)	92 (92)
2	C_6H_5-Br	0.075	2 (2)	90 (88)
3	C_6H_5-Br	0.05	4 (4)	85 (85)
4	C_6H_5-Cl	0.075	12 (12)	64 (65)
5	C_6H_5-Cl	0.05	12 (12)	45 (45)
6	4-O_2N-C_6H_4-I	0.05	0.75 (0.75)	92 (92)
7	4-O_2N-C_6H_4-Br	0.05	1.5 (1.5)	86 (85)
8	4-MeO-C_6H_4-I	0.05	7 (7)	86 (85)
9	4-MeO-C_6H_4-Br	0.075	12 (12)	65 (63)
10	2-Me-C_6H_4-I	0.05	3 (3)	82 (80)
11	2-Iodothiophene	0.05	7 (7)	85 (84)

[a] Reaction conditions: aryl halide (1 mmol), alkyne (1.2 mmol), triethylamine (4 mmol), acetonitrile (3 mL) under reflux conditions

[b] Isolated yield

[c] The times and yields in parenthesis related to PNP-SBNPP

(Table 2, entries 6, 7). Iodothiophene was also found to react smoothly with phenylacetylene in very good yield (Table 2, entry 11). PNP-SBNPP was shown the same efficiency with PNP-SBPPSP in most cases, but as the Pd contents of PNP-SBNPP is slightly more {PNP-SBPPSP 0.05 g (2.6 mol % of Pd) [or PNP-SBNPP 0.05 g (2.8 mol %)]} so the reactivity of PNP-SBNPP is lower than PNP-SBPPSP.

The possibility of recycling the catalyst was examined using the reaction of iodobenzene with phenylacetylene under optimized conditions. Upon completion, the reaction mixture was filtered and the catalyst was washed with dichloromethane. The recycled catalyst could be reused four times without any treatment (Fig. 5).

Conclusions

In conclusion, this work shows that palladium nanoparticles stabilized by silica-bonded *N*-propylpiperazine sodium *N*-propionate, which can be prepared by simple operation

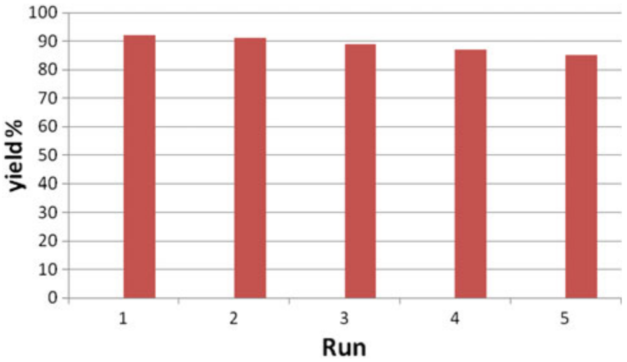


Fig. 5 Recyclability of PNP-SBPPSP in the reaction of iodobenzene (2 mmol), phenylacetylene (2.4 mmol), triethylamine (8 mmol) and acetonitrile (5 mL) under reflux conditions. Reaction time = 1.0 h

from commercially available and relative cheap starting materials, efficiently catalyzed the Sonogashira reactions. It could also be recovered and reused for several times without noticeable loss of reactivity.

Acknowledgments We are thankful to Persian Gulf University Research Council for partial support of this work. Also, we are thankful to the School of Chemistry, Manchester University for running CHN and SEM.

References

1. R. Chinchilla, C. Najera, Chem. Soc. Rev. **40**, 5084 (2011)
2. K. Sonogashira, Y. Tohda, N. Hagihara, Tetrahedron Lett. **16**, 4467 (1975)
3. R. Chinchilla, C. Najera, Chem. Rev. **107**, 874 (2007)
4. H. Plenio, Angew. Chem. Int. Ed. **47**, 6954 (2008)
5. P. Siemsen, R.C. Livingston, F. Diederich, Angew. Chem. Int. Ed. **39**, 2632 (2000)
6. V.P.W. Bohm, W.A. Herrmann, Eur. J. Org. Chem. **200**, 3679 (2000)
7. T. Suzuka, Y. Okada, K. Ooshiro, Y. Uozumi, Tetrahedron **66**, 1064 (2010)
8. S. Roy, H. Plenio, Adv. Synth. Catal. **352**, 1014 (2010)
9. Y. He, C. Cai, J. Organometal. Chem. **696**, 2689 (2011)
10. A.N. Marziale, J. Schluter, J. Eppinger, Tetrahedron Lett. **52**, 6355 (2011)
11. D. Astruc (ed.), *Nanoparticles and Catalysis* (Wiley-VCH, Weinheim, 2008)
12. S. Moussa, A.R. Siamaki, B.F. Gupton, M.S. El-Shall, ACS Catal. **2**, 145 (2012)
13. J. Cheng, G. Zhang, J. Du, L. Tang, J. Xu, J. Li, J. Mater. Chem. **21**, 3485 (2012)
14. K. Niknam, M.S. Habibabad, A. Deris, F. Panahi, M.R. Hormozi Nezhad, J. Iran. Chem. Soc. **10**, 527 (2013)
15. B. Karimi, S. Abedi, J.H. Clark, V. Budarin, Angew. Chem. Int. Ed. **45**, 4776 (2006)
16. V. Polshettiwar, C. Len, A. Fihri, Coord. Chem. Rev. **253**, 2599 (2009)
17. J. Demel, J. Cejka, P. Stepnicka, J. Mol. Catal. A: Chem. **329**, 13 (2010)
18. D. Astruc, Tetrahedron Asymmetry **21**, 1041 (2010)
19. H. Firouzabadi, N. Iranpoor, M. Gholinejad, J. Organometal. Chem. **695**, 2093 (2010)
20. A. Corma, S. Iborra, F.X.L.I. Xamena, R. Monton, J.J. Calvino, C. Prestipino, J. Phys. Chem. C **114**, 8828 (2010)
21. K. Niknam, A. Gharavi, M.R. Hormozi-Nezhad, F. Panahi, M.T. Sharbati, Synthesis 1609 (2011)
22. A. Khalafi-Nezhad, F. Panahi, Green Chem. **13**, 2408 (2011)
23. R. Richard, *Surface and Nanomolecular Catalysis* (Taylor & Francis, London, 2006)
24. H. Firouzabadi, N. Iranpoor, F. Kazemi, M. Gholinejad, J. Mol. Catal. A: Chem. **357**, 154 (2012)
25. H. Firouzabadi, N. Iranpoor, A. Ghaderi, M. Ghavami, S.J. Hoseini, Bull. Chem. Soc. Jpn. **84**, 100 (2011)
26. J. Wang, B. Xu, H. Sun, G. Song, Tetrahedron Lett. **54**, 238 (2013)
27. J. Zhang, W. Zhang, Y. Wang, M. Zhang, Adv. Synth. Catal. **350**, 2065 (2008)
28. K. Niknam, A. Deris, F. Naeimi, F. Majleci, Tetrahedron Lett. **52**, 4642 (2011)
29. R.K. Dey, T. Patnaik, V.K. Singh, S.K. Swain, C. Airoldi, Appl. Surf. Sci. **255**, 8176 (2009)
30. M. Lamblin, L. Nassar-Hardy, J.C. Hierso, E. Fouquet, F.X. Felpin, Adv. Synth. Catal. **352**, 33 (2010)