Short Communication

# Palladium supported on amine-functionalized mesoporous silica: Highly efficient phosphine-free catalyst for alkyne–alkyne cross-coupling reaction

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### ARTICLE INFO

### ABSTRACT

An amine-functionalized mesoporous silica SBA-15 supported palladium catalyst was prepared and characterized. For the first time, this supported palladium has been used as an efficient phosphine-free and reusable catalyst for the cross-coupling of haloalkynes with terminal alkynes. A variety of haloalkynes and aromatic/aliphatic terminal alkynes were selectively coupled to afford unsymmetrical 1,4-disubstituted 1,3-diynes in good yields.

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## 1. Introduction

Conjugated diynes are important building blocks in natural products, pharmaceutical intermediates, nonlinear optical materials and liquid crystals [1–5]. As a result, artificial synthesis of diyne derivatives has attracted much attention [1,3,6–8]. Cu-salt mediated Glaser coupling and its modifications are the major methods to prepare symmetrical diynes [9–12]. Cadiot–Chodkiewicz coupling and related modified methods, Cu-catalyzed cross-couplings between a haloalkyne and a terminal alkyne, are widely used for constructing unsymmetrical diynes [13–16]. Palladium catalysts have also been developed for heterocoupling of a haloalkyne and a terminal alkyne [17–22]. To improve the yield and selectivity, Alami et al. introduced palladium/phosphine complex $PdCl_2(PPh_3)_2$ into the $C(sp)$–$C(sp)$ cross-coupling reactions for the preparation of unsymmetrical diynes [18]. However, these reactions often suffer from poor selectivity and lead to a considerable amount of homo-coupled byproducts. Thus, excessive amount of alkynes (up to 5 equivalents) is necessary to enhance the selectivity of cross-coupled products [1,3,6,17]. Recently, Lei et al. have successfully developed a highly efficient method by using a π-acceptor phosphine ligand/Pd as the catalyst to prepare unsymmetrical 1,3-diynes [23]. However, efficient phosphine-free palladium catalysts for the alkyne–alkyne cross-coupling reactions have not been explored [17].

Because of their advantages such as the easy handling and good recyclability, heterogeneous catalysts are usually the first choice for constructing a new catalytic system. In recent years, mesoporous silica materials as catalyst supports for synthetic organic chemistry have attracted much attention, due to their well-defined micro-structure that forms the basis of uniform active sites of the catalyst and well-controlled steric effects [24]. Among them, SBA-15 has been widely used as support for palladium catalysts [25]. However, a supported palladium as the catalyst for the synthesis of unsymmetrical diynes has not been studied yet. Triethylenediamine, an inexpensive commercially available ligand, has been successfully used in the Suzuki cross-coupling reaction [26]; thus we envisioned that triethylenediamine may work in the alkyne–alkyne cross-coupling reaction. In continuation of our interest in exploring phosphine-free catalytic systems for C—C bond formation [27–29], an amine-functionalized mesoporous silica SBA-15 supported palladium has been successfully applied for alkyne–alkyne cross-coupling reactions with high selectivity.

## 2. Experimental methods

### 2.1. Catalyst preparation

As shown in Scheme 1, Cl-SBA-15 [30] and Amine-SBA-15 [31] were prepared according to the reported method. Firstly, SBA-15 (1 g, BET surface area = 554.7 $m^2g^{-1}$ and pore size = 6.0 nm) was dispersed in boiling toluene (25 mL) and then (3-chloropropyl) trimethoxysilane (1.5 mL) was added dropwise. The mixture was refluxed for 24 h. After cooling, the suspension was filtered and the

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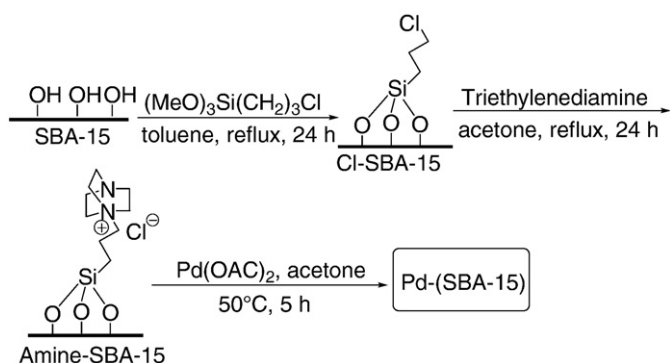
Scheme 1. Schematic diagram of Pd-(SBA-15) preparation.



Fig. 2. TEM image of Pd-(SBA-15).

solid residue was extracted thoroughly in a Soxhlet extractor with dichloromethane before being dried in vacuum at 70 °C for 5 h. Secondly, Cl-SBA-15 (1 g) was refluxed with triethylenediamine (73 mg) in acetone (60 mL) for 24 h under argon atmosphere. The resulting solid powder was recovered by filtration and extracted with dichloromethane in a Soxhlet extractor overnight and then dried in vacuum at 50 °C for 4 h. The white powder, designated as Amine-SBA-15, was collected (BET surface area = 392.7 m$^2$g$^{-1}$, pore size = 5.8 nm and elemental analysis of nitrogen = 1.04 mmol g$^{-1}$). Finally, Amine-SBA-15 (1 g) was refluxed with Pd(OAc)$_2$ (117.6 mg) in acetone (30 mL) at 50 °C for 5 h. After filtration, the solid powder was washed three times with ethyl ether (10 mL) and methanol (10 mL), respectively, and then dried under air. The yellow powder was collected and designated as Pd-(SBA-15) (BET surface area = 353.8 m$^2$g$^{-1}$, pore size = 5.5 nm and 4.06% Pd based on ICP-AES).

## 2.2. Catalyst characterization

The as-synthesized materials were characterized by means of the elemental analysis, ICP-AES, XRD, HRTEM, BET and XPS techniques. The detailed procedures were described in Appendix A. The conversion was determined by gas chromatography (GC7890II, Techcomp) analysis equipped with a SE-54 column and a flame ionization detector (FID) using biphenyl as an internal standard.

## 2.3. Catalytic reactions

Typically, a mixture of bromoethynylbenzene (0.5 mmol), 2-methylbut-3-yn-2-ol (0.6 mmol), Pd-(SBA-15) (2 mol%), CuI (2.0 mol%), Et$_3$N (2 eq.) and DMF (1 mL) was stirred at room temperature under argon atmosphere for the desired time. The reaction mixture was then centrifuged and washed with ethyl acetate. The combined organic phase was dried over anhydrous Na$_2$SO$_4$ and concentrated under vacuum. The residue was purified by flash
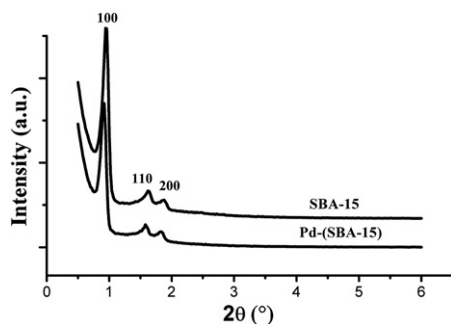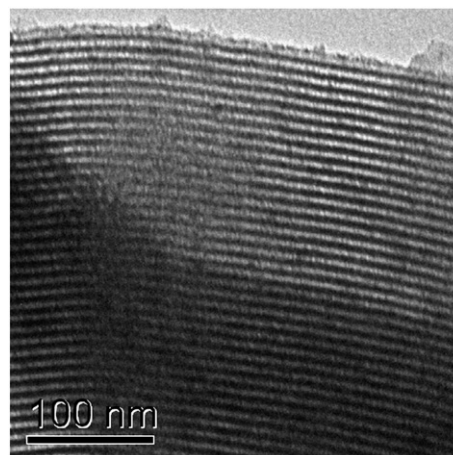
chromatography on silica gel (ethyl acetate/hexane) to afford the pure product. After the first reaction cycle, the catalyst was recovered by centrifugation and filtration. After being washed by deionized water and ethyl acetate, respectively, the recovered catalyst was dried under vacuum and then might be directly used for the next cycle. The identification was conducted by GC analysis and $^1$H NMR measurement.

## 3. Results and discussion

### 3.1. Catalyst characterization results

XRD analysis of SBA-15 before and after the modification both showed a strong peak at 0.8° and two weak peaks around 1.45° and 1.65°, which were assigned to 1 0 0, 1 1 0 and 2 0 0 reflections of the ordered periodic arrangement of hexagonal channels (Fig. 1), implying that the mesoporous structure of the carrier was not deteriorated after introduction of ligands and Pd [32]. The HRTEM morphology further confirmed that the Pd-(SBA-15) had well-ordered mesostructure as shown in Fig. 2. Nitrogen adsorption–desorption isotherms of SBA-15, Amine-SBA-15 and Pd-(SBA-15) (Fig. 3) exhibited typical IV type isotherm pattern with an H2 hysteresis loop, implying the characteristic of the mesoporous structure is remained. Step-wise desorption of N$_2$ can be clearly seen for freshly prepared Pd-(SBA-15) (Fig. 3), which might be attributed to the physical adsorption of N$_2$ on Pd nanoparticles [33]. The values of the surface area and pore volume gradually decrease with introduction of triethylenediamine and Pd, suggesting the ligands and Pd are successfully anchored to the pore channels. XPS analysis
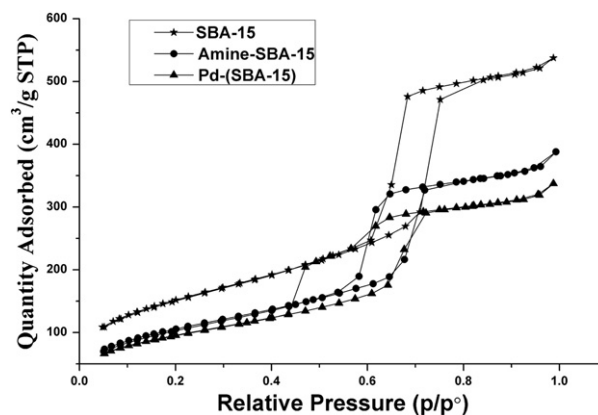


Fig. 1. Low-angle XRD patterns of SBA-15 and Pd-(SBA-15).



Fig. 3. N$_2$ sorption isotherms: (a) SBA-15; (b) Amine-SBA-15; (c) Pd-(SBA-15).
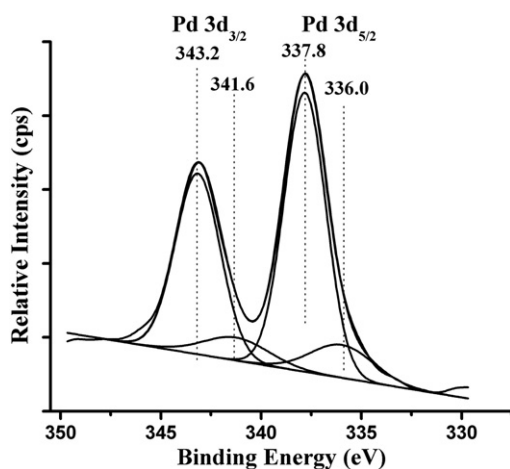
Fig. 4. XPS spectra of the Pd 3d$_{5/2}$ and 3d$_{3/2}$ electrons' binding energies for Pd-(SBA-15).
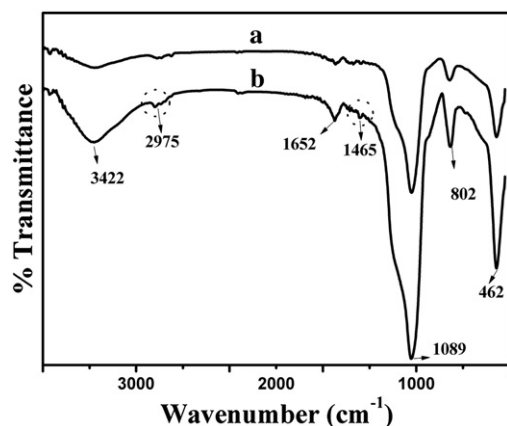


Fig. 5. FT-IR spectra: (a) Cl-SBA-15; (b) Amine-SBA-15.

showed that the fresh Pd-(SBA-15) catalyst consists of both Pd(II) and Pd(0) and the ratio of Pd(II) to Pd(0) was about 3.5:1 (Fig. 4). As shown in Fig. 4, the measured binding energies of the Pd 3d$_{5/2}$ and 3d$_{3/2}$ electrons at 337.8 and 343.2 eV, respectively corresponding to Pd(II) [34]. In addition, a weak contribution on the Pd 3d peak was also distinguishable at 336.0 and 341.6 eV ascribed to the presence of Pd(0) species. The existence of triethylenediamine group could also be confirmed by the FT-IR spectrum (Fig. 5). Both Cl-SBA-15 and Amine-SBA-15 materials showed characteristic bands at 1652 cm$^{-1}$ the O–H stretching vibration and bands at 1089, 802 and 462 cm$^{-1}$ due to the Si–O stretching vibration. FT-IR spectrum of Amine-SBA-15 (Fig. 5b) exhibited two bands at 2975 cm$^{-1}$ and 1465 cm$^{-1}$, assigned to the C–H stretching vibration and C–N bending vibration of triethylenediamine group, respectively [35]. These two peaks are not observed in the spectrum of the Cl-SBA-15 (Fig. 5a).

### 3.2. Pd-(SBA-15) catalyzed cross-coupling reaction of terminal alkynes

As shown in Table 1, the reaction of bromoethynylbenzene (**1a**) and 2-methylbut-3-yn-2-ol (**2a**) was chosen as the model and effects of different parameters were examined to figure out the optimum condition. Different catalytic system were firstly tested in the presence of Et$_3$N (2 Eq), CuI (2 mol%) and DMF (1 mL) at room temperature. Pd(OAc)$_2$ (2 mol%) as the catalyst afforded **3a** in a yield of 36% (entry 1). It was noteworthy that when Pd-(SBA-15) (1 mol%) was utilized as the catalyst, **3a** was obtained in 76% yield along with only 5% 1,4-diphenylbutadiyne product (entry 2). Further increase the loading of Pd-(SBA-15) to 2 mol%, the yield of **3a** was improved to 88% (entry 3). Trace desired product **3a** was obtained when Amine-SBA-15 (2 mol%) as the catalyst (entry 4). The mixture of Pd(OAc)$_2$ (2 mol%) and the equal amounts of SBA-15 and/or triethylenediamine as the catalysts were less effective than that of 2 mol% Pd-(SBA-15) (entries 5–7). Further optimization indicated that CuI was crucial in this reaction as well. When the amount of CuI decreased to 1 mol%, the yield of **3a** decreased to 53%, while without CuI, only 9% **3a** was got and the selectivity dropped to 50% (entries 8 and 9). Moreover, the effects of solvent and base were also studied (entries

### Table 1

Effect of various parameters on the reaction of bromoethynylbenzene (**1a**) and 2-methylbut-3-yn-2-ol (**2a**).[a]
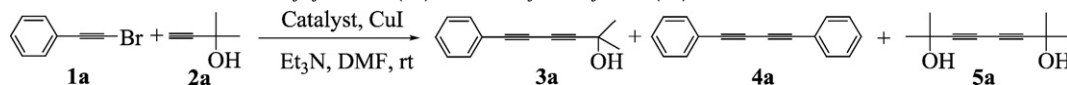


| Entry | Catalyst (mol%) | Solvent | Time (h) | Conv. (%)[b] | 3a Yield (%)[b] | 3a Selectivity (%) |
|---|---|---|---|---|---|---|
| 1 | Pd(OAc)$_2$ (2) | DMF | 5.5 | 100 | 36 | – |
| 2 | Pd-(SBA-15) (1) | DMF | 16 | 100 | 76 (72) | 91 |
| 3 | Pd-(SBA-15) (2) | DMF | 16 | 100 | 88 (79) | 92 |
| 4 | Amine-SBA-15 (2) | DMF | 15 | 48 | <1 | – |
| 5 | Pd(OAc)$_2$ (2)/SBA-15 | DMF | 15 | 100 | 57 | 91 |
| 6 | Pd(OAc)$_2$ (2)/ triethylenediamine | DMF | 16 | 100 | 67 | 92 |
| 7 | Pd(OAc)$_2$ (2)/SBA-15/ triethylenediamine | DMF | 16 | 100 | 73 (70) | 92 |
| 8[c] | Pd-(SBA-15) (2) | DMF | 15 | 100 | 53 | 93 |
| 9[d] | Pd-(SBA-15) (2) | DMF | 15 | 93 | 9 | 50 |
| 10 | Pd-(SBA-15) (2) | CH$_3$CN | 12 | 100 | 52 | 68 |
| 11 | Pd-(SBA-15) (2) | THF | 12 | 100 | 51 | 68 |
| 12[e] | Pd-(SBA-15) (2) | DMF | 15 | 100 | 72 (67) | 84 |
| 13[f] | Pd-(SBA-15) (2) | DMF | 15 | 100 | 33 | 72 |

[a] Reaction conditions: **1a** (0.5 mmol), **2a** (0.6 mmol), catalyst, Et$_3$N (2 eq.), CuI (2 mol%), and solvent (1 mL) at room temperature.
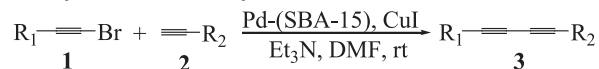[b] Determined by GC using biphenyl as internal standard and numbers in parentheses are the isolated yields.
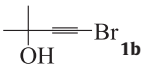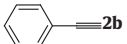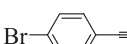[c] CuI (1 mol%).
[d] Without CuI.
[e] Triethylenediamine as the base.
[f] Piperidine as the base.
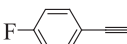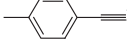
**Table 2**
Pd-(SBA-15) catalyzed cross-coupling reactions of haloalkynes with terminal alkynes.[a]

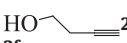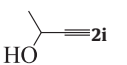$$R_1 \!\!=\!\! Br \ + \ \!\!=\!\! R_2 \xrightarrow[\text{Et}_3\text{N, DMF, rt}]{\text{Pd-(SBA-15), CuI}} R_1 \!\!=\!\!\!=\!\! R_2$$

| Entry | Substrate **1** | Substrate **2** | Time (h) | Yield (%)[b] |
|---|---|---|---|---|
| 1 | **1a** | **2a** | 16 | **3a**, 79, 88[c] |
| 2 | **1b** | **2b** | 12 | **3a**, 87[c] |
| 3 | **1b** | **2c** | 24 | **3b**, 73 |
| 4 | **1b** | **2d** | 8 | **3c**, 88 |
| 5 | **1b** | **2e** | 7.5 | **3d**, 81 |
| 6 | **1b** | **2f** | 15 | **3e**, 90 |
| 7 | **1b** | **2g** | 24 | **3f**, 61 |
| 8 | **1b** | **2h** | 24 | **3g**, 85 |
| 9 | **1a** | **2f** | 24 | **3h**, 78 |
| 10 | **1a** | **2h** | 16 | **3i**, 75 |
| 11 | **1a** | **2i** | 24 | **3j**, 74 |

[a] Reaction conditions: **1** (0.5 mmol), **2** (0.6 mmol), Pd-(SBA-15) (2 mol%), Et$_3$N (2 eq.), CuI (2 mol%), and DMF (1 mL) at room temperature.
[b] Isolated yield.
[c] Determined by GC using biphenyl as internal standard.

10–13). The results showed that when DMF was chosen as the solvent and Et$_3$N as the base higher yield and selectivity were obtained.

To evaluate the substrate scope, we examined the protocol employing various 1-bromoalkynes and terminal alkynes (Table 2). The results showed Pd-(SBA-15) was tolerant of a variety of functional groups including –OH, –F, –Br, –Cl and –CH$_3$. It is interesting to note that the cross-coupling of 1-ethynyl-4-fluorobenzene (**2c**) and 4-bromo ethynylbenzene (**2d**) with 4-bromo-2-methylbut-3-yn-2-ol (**1b**) selectively afforded desired unsymmetrical diynes **3b** (73% yield) and **3d** (88% yield), respectively (entries 3 and 4). No dehalogenation proceeded in the case of halogen-substituted ethynylbenzene derivatives (**2c** and **2d**), which gives an opportunity for further functionalization at the intact halide group in the product diynes. A number of aliphatic terminal alkynes with different functional groups such as hex-5-yn-1-ol (**2f**), 5-chloropent-1-yne (**2g**) and but-3-yn-1-ol (**2h**) reacted smoothly with 4-bromo-2-methylbut-3-yn-2-ol (**1b**), providing corresponding products **3e**, **3f**, **3g** in 90, 61 and 85% yields, respectively (entries 6–8). It also worked well for the cross-coupling reactions of bromoethynylbenzene (**1a**) and aliphatic terminal alkynes bearing a hydroxyl group including **2f**, **2h** and but-3-yn-2-ol (**2i**) (entries 9–11).

Reusability of Pd-(SBA-15) was then investigated through the cross-coupling reaction of 4-bromo-2-methylbut-3-yn-2-ol (**1b**) and phenylacetylene (**2b**). Pd-(SBA-15) was found to be easily separated from the reaction mixture by simple filtration. The recovered catalyst was then reused for the reaction of **1b** and **2b** under conditions exactly same as those of the first run except the catalyst. Pd-(SBA-15) showed very good reusability. Under the reaction conditions shown in Table 2, the yields of the cross-coupling reaction of **1b** and **2b** from the 1st run to the 3rd run were 90%, 90% and 65%, respectively.

## 4. Conclusions

An amine-functionalized mesoporous silica SBA-15 supported palladium has been successfully utilized as an efficient phosphine-free, reusable catalyst for the cross-coupling of haloalkynes with terminal alkynes to afford the corresponding unsymmetrical diynes. Tolerant of a variety of functional groups, this new protocol had a broad substrate scope including haloalkynes and aromatic as well as aliphatic terminal alkynes. Under mild condition, the reaction could be performed with high conversion and chemoselectivity without using large excessive amount of one substrate. These advantages make the present catalytic procedure an attractive option for the synthesis of unsymmetrical 1,3-diynes.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.catcom.2011.10.027.

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