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# Heterogeneous palladium catalyst constructed with cross-linked hyperbranched poly(phenylacetylene) as polymer support: A reusable highly active ppm-level catalyst for multiple cross-coupling reactions

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ABSTRACT

We demonstrate in this work a unique strategy for the synthesis of heterogeneous Pd catalysts with the use of a hyperbranched poly(phenylacetylene) containing pendant alkyne groups as the cross-linkable polymer substrate. It utilizes the dual functions of Pd-based catalysts in catalyzing both alkyne polymerization/oligomerization and coupling reactions. In the synthesis, a homogeneous Pd(II) catalyst catalyzes the cross-linking of the hyperbranched polymer and simultaneously encapsulates itself into the cross-linked polymer matrix, rendering the heterogeneous catalyst at high yield and high percentage of Pd encapsulation. Three homogeneous catalysts having different ligands (triphenylphosphine, a diphosphine ligand, and a diimine ligand) have been examined for the cross-linking encapsulation and the resulting heterogeneous catalysts have been evaluated for their catalytic performance in coupling reactions. Among the various heterogeneous catalysts obtained, a triphenylphosphine-ligated catalyst, HBPPA-Pd-2, appears to be the optimum one. It shows high activity in catalyzing the Suzuki–Miyaura reactions, the Mizoroki–Heck reactions, and the allylic arylation reactions under air with the Pd loading at as low as mol ppm or even mol ppb levels relative to the reactants. Meanwhile, it facilitates the Suzuki–Miyaura reactions of challenging less reactive aryl chlorides/heteroaryl bromides and the Mizoroki–Heck reactions of aryl bromides as reactants. In addition, it behaves truly as a heterogeneous catalyst with high reusability and low catalyst leaching during the reactions.

## 1. Introduction

Palladium-catalyzed carbon–carbon cross-coupling reactions [1–3], including the notable Suzuki–Miyaura [4–7] and Mizoroki–Heck reactions [8–13], have played an important role in modern organic synthesis by enabling many valuable organic transformations. Due to the high cost of Pd as well as environmental and health issues, reusable heterogeneous Pd catalysts have drawn increasing attention for the industrial applications of these coupling reactions since homogeneous Pd catalysts are difficult to recover and reuse. Numerous heterogeneous catalysts have been developed with the use of various organic polymeric and inorganic supports through different catalyst immobilization/encapsulation strategies [14–22]. But the search is continuing for high-performance heterogeneous catalysts of high activity with Pd loading needed at as low as ppm levels, high reusability with minimum/negligible catalyst leaching during reactions, and high versatility with broad applicability to multiple types of coupling reactions and to difficult precursors such as aryl chlorides [23]. Such heterogeneous catalysts of combined performance properties are still limited despite the enormous investigations in the area.

Relative to the inorganic supports, organic polymer supports show the advantage in their convenient synthesis and the versatility in tuning their composition/functionality for controllable catalyst immobilization/encapsulation. A great variety of polymers, including both soluble polymers [24–28] with controllable linear [16,19,24–28] or dendritic/hyperbranched architectures [29–33] and insoluble polymers [14–22], have been used as the substrate for the immobilization/encapsulation of various Pd complexes or Pd nanoparticles. With soluble polymer substrates, high catalyst activity can be achieved due to their soluble nature, but at the compromise of relatively higher catalyst leaching and the requirement of special catalyst recovery methods such as biphasic solvent systems and polymer precipitation with proper solvents [24–28]. On the contrary, heterogeneous catalysts on insoluble polymers offer much more convenient catalyst recovery and reuse

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through simple procedures like filtration. In particular, insoluble cross-linked polymers show the further added advantage of reduced catalyst leaching because the tightly cross-linked 3-dimensional networks minimize the aggregation and leaching of the encapsulated catalyst species. Due to these advantages, various insoluble cross-linked polymers have been developed and used to immobilize/encapsulate Pd nanoparticles and Pd complexes as heterogeneous catalysts [17,18,34]. They include broadly cross-linked amphiphilic copolymer micelles [17,18,35–37], cross-linked polymethacrylates [38,39], cross-linked polystyrene-poly(ethylene glycol) resins [40–42], cross-linked poly(amidoamine) dendrimers [43], polyurea [44,45], self-assembled poly(imidazole) via binding with Pd species [46,47], cross-linked hyperbranched polyethylenes with self-supported Pd nanoparticles [48], cross-linked microporous polymers [49–51], cross-linked reverse micelle [52], cross-linked polystyrenes with different covalently tethered functionalities [53–56], cross-linked ionic copolymers [57–59], hydrogels [60,61], cross-linked chitosan [62,63], cross-linked poly(1,3-diethynylbenzene) [64], etc.

The majority of heterogeneous Pd catalysts on cross-linked polymer supports have been synthesized via stepwise procedures comprised of the synthesis of the cross-linked polymers with desired functionalities followed with catalyst immobilization. With this synthetic strategy, the immobilized Pd catalysts are thus bound either covalently or noncovalently on the internal surface of the cross-linked polymer substrates instead of being incorporated within the polymer matrix. This increases the risk of catalyst leaching. Only in some cases [35–37,41,43–48,52,62–64] the Pd catalysts are embedded desirably within the cross-linked polymer matrix wherein Pd encapsulation occurs during or prior to polymer cross-linking in the synthesis. Meanwhile, the majority of the heterogeneous catalysts on cross-linked polymer supports show relatively low activity with a large Pd loading often required to facilitate the coupling reactions, and often have limited applicability to only one or two types of couple reactions.

In this article, we report a convenient alternative one-step synthetic strategy that leads to a reusable, high-activity, high-versatility heterogeneous catalyst with Pd species encapsulated within a cross-linked hyperbranched poly(phenylacetylene) (HBPPA) matrix. Different from all other previously reported syntheses, a triphenylphosphine-ligated cationic Pd catalyst is herein used as an alkyne polymerization catalyst to cross-link the hyperbranched poly(phenylacetylene) having pendant alkyne groups. During the cross-linking, the Pd catalytic species are simultaneously embedded within the formed polymer networks, turning themselves uniquely from a homogeneous polymerization catalyst into a heterogeneous cross-coupling catalyst. The heterogeneous catalyst synthesized herein has been found to efficiently catalyze the Suzuki–Miyaura, Mizoroki–Heck, and allylic arylation reactions at the Pd loadings of as low as ppm levels relative to reactants, as well as good reusability with low catalyst leaching during the reactions.

## 2. Experimental

### 2.1. Materials

All manipulations and reactions were performed under atmospheric conditions unless otherwise noted. In order to avoid the influence of any residual Pd species absorbed on the surface, all the glassware and magnetic stirrers used for cross-coupling reactions were pre-treated with aqua regia, then washed with distilled water before being dried. The acetonitrile Pd-diimine catalyst, $[(ArN{=}C(Me){-}(Me)C{=}NAr)Pd(CH_3)(N{\equiv}CMe)]^+SbF_6^-$ (Ar = 2,6-$(i\mathrm{Pr})_2C_6H_3$), was synthesized according to a literature procedure [65]. HPLC-grade $CH_2Cl_2$ (99.5%, Fisher Scientific) was deoxygenated and dried by using a solvent purification system (Innovative Technology) before use. Methanol (ACS reagent, Fisher Scientific) was dried with 3 Å/5 Å molecular sieves before use. Deionized Water was obtained from a Barnstead/SynbronNanopure II water purification system. A palladium atomic absorption standard solution, containing 1011 ppm of Pd in 5.1 wt% HCl, was purchased from Aldrich. *N*,*N*-dimethylformamide (DMF, certified ACS grade), tetrahydrofuran (THF, certified grade), hydrochloric acid (35–38 wt.% in water), KF (granular powder, certified ACS grade) and $K_2CO_3$ (granular powder, certified ACS grade) were received from Fisher Scientific and used without further purification. Palladium (II) acetate ($Pd(OAc)_2$, 98%) and $\alpha,\alpha'$-bis(di-*t*-butylphosphino)-*o*-xylene (97%) were obtained from Strem Chemicals and used as received. Mesoporous silica SBA-15 was purchased from Claytec Inc., and was vacuum dried at 160 °C for 8 h before use. All other chemicals or solvents, including 1-methyl-2-pyrrolidinone (NMP, ReagentPlus), CsF (>99%), 1,3-diethynylbenzene (DEB, 96%), methanesulfonic acid (MSA, 99.5%), triphenyl phosphine ($PPh_3$, 99%), iodobenzene (PhI, 98%), 4′-iodoacetophenone (98%), bromobenzene (PhBr, 99%), 1-bromo-4-nitrobenzene (99%), 4-bromobenzonitrile (99%), 4′-bromoacetophenone (98%), 4-bromoanisole (99%), 4-bromotoluene (98%), 2-bromotoluene (99%), 3-bromotoluene (98%), 2-bromomesitylene (98%), 1-bromonaphthalene (97%), 2-bromopyridine (99%), 3-bromothianaphthene (95%), chlorobenzene (PhCl, ReagentPlus), 4′-chloroacetophenone (97%), 4-chlorotoluene (98%), 4-chloroanisole (99%), 4-chlorobenzonitrile (99%), 4-methoxyphenylboronic acid (≥95%), 4-acetylphenylboronic acid, *n*-butyl acrylate (BA, >99%), styrene (99%), triethyl amine ($Et_3N$, 99%), phenylboronic acid (PBA, >97%), cinnamyl acetate (99%), prenyl acetate (≥98%), sodium tetraphenylborate ($NaBPh_4$, ACS Reagent), nitric acid ($HNO_3$, 70%), and hydrogen peroxide ($H_2O_2$, 50 wt.% in water), were all purchased from Aldrich and used as received.

### 2.2. Measurements and characterizations

The characterization of HBPPA with gel permeation chromatography (GPC) was carried out on a Polymer Laboratories PL-GPC220 system equipped with a triple-detection array comprising of a differential refractive index (DRI) detector (from Polymer Laboratories), a three-angle (45, 90, and 135°) light scattering (LS) detector (from Wyatt Technology) at a laser wavelength of 687 nm, and a four-bridge capillary viscosity detector (from Polymer Laboratories). Details in the characterization have been reported in our earlier paper [66].

All measurements with proton nuclear magnetic resonance ($^1H$ NMR) spectroscopy were carried out on a Bruker AV500 spectrometer (500 MHz) at ambient temperature with $CDCl_3$ as solvent. Atomic absorption (AA) spectroscopy was performed on a Perkin Elmer Precisely AAnalyst 400 spectrometer (Perkin Elmer) equipped with a Pd element lamp (max. 30 mA, Perkin Elmer). The data was collected with a WinLab32 software (Perkin Elmer). The blank solution for the preparation of the standard Pd solutions and sample dilution was composed of 11.1 vol% THF, 6.7 vol% HCl, and 3.4 vol% $H_2O_2$ in deionized water. For all the analyses, a calibration curve was first established with Pd standard solutions with [Pd] in the range of 0.25–10 mg/L. X-ray photoelectron spectroscopy (XPS) measurements of the heterogeneous Pd catalysts were carried out on a Thermo Scientific Theta Probe XPS spectrometer (ThermoFisher). A monochromatic Al Kα X-ray source was used, with a spot area 400 μm. The samples were run in a standard mode, i.e., all angle collected (60° angular acceptance) for the survey spectra, and for the region spectra. Transition electron

**Table 1**
Heterogeneous Pd catalysts by Pd-catalyzed cross-linking of HBPPA.[a]

| Heterogeneous Pd catalyst | Catalyst for cross-linking | [alkyne]/[Pd] | yield%[b] | $Pd_{enc}$%[c] | Pd%[c] |
|---|---|---|---|---|---|
| HBPPA-Pd-1 | L1-Pd | 4.4 | 93 | 75 | 2.6 |
| HBPPA-Pd-2 | L1-Pd | 8.8 | 96 | 97 | 1.9 |
| HBPPA-Pd-3 | L1-Pd | 26 | 98 | 97 | 0.6 |
| HBPPA-Pd-4 | L2-Pd | 8.8 | 77 | 68 | 1.7 |
| HBPPA-Pd-5 | L3-Pd | 8.8 | 88 | 92 | 1.9 |

[a] Other conditions: [alkyne] = 0.14 M (HBPPA: 0.52 g), $CH_2Cl_2$/MeOH (v/v = 10:1) as solvent (5.5 mL), reaction at room temperature. L1-Pd:$Pd(OAc)_2$/triphenylphosphine (L1) at the [Pd]/[L1] ratio of 1: 6; L2-Pd: $Pd(OAc)_2$/diphosphine (L2) at the [Pd]:[L2] ratio of = 1: 3; L3-Pd: acetonitrile Pd–diimine catalyst.

[b] Yield of the heterogeneous catalyst calculated on the basis of weight relative to HBPPA.

[c] Percentage of encapsulated Pd relative to the feed Pd($Pd_{enc}$%) and weight content of Pd in the heterogeneous catalysts (Pd%) were determined via atom absorption analysis of each heterogeneous catalyst.

microscopy (TEM) images were collected on a JEOL 2010F field emission electron microscope operated at 200 keV.

### 2.3. Synthesis of hyperbranched polyphenylacetylene (HBPPA)

The HBPPA containing pendant alkyne groups was synthesized according to our earlier paper [66]. Under $N_2$ protection, $Pd(OAc)_2$ (7.1 mg, 32 μmol), α,α'-bis(di-*t*-butylphosphino)-*o*-xylene (38 mg, 96 μmol), and methanol (8 mL) were mixed in a sealed 20 mL glass vial and sonicated at room temperature until all the solids were dissolved to form the catalyst solution. In the meantime, a flame-dried Schlenk flask was charged with PA (1.02 g, 10 mmol), DEB (0.374 g, 3 mmol), one drop of methanesulfonic acid (MSA, ca. 0.05 mL), and $CH_2Cl_2$ (30 mL) under nitrogen protection. The flask was shielded with aluminum foil before the catalyst solution was injected. The mixture was stirred under $N_2$ atmosphere for 3 h at room temperature. At the completion of the polymerization, the reaction mixture was poured into 2%-acidified methanol (ca. 300 mL) to terminate the polymerization and precipitate out the polymer. The orange polymer precipitate underwent a redissolution–precipitation procedure for 3 cycles to remove the catalyst and monomer residues. Finally, the polymer was dried under vacuum at room temperature for 24 h and then weighed (0.84 g, yield: 60%). Triple-detection GPC characterization: number-average molecular weight, $M_n = 27.2$ kg/mol; polydispersity index, PDI = 1.57 (both measured with light scattering detector); Mark–Houwink exponent, $\alpha = 0.20$. $^1H$ NMR characterization: DEB content in the copolymer, 23 mol%; percentage of dual-inserted DEB, 29%; content of the pendent alkyne groups, 41 alkyne group per chain or 1.5 mmol/g; branching density, 6.7 mol% (number of dual-inserted DEB/the number of all inserted monomer units × 100%).

### 2.4. Synthesis of heterogeneous Pd catalysts with cross-linked HBPPA as polymer support

A typical synthetic procedure (for HBPPA-Pd-2 in Table 1) is as follows. HBPPA (0.52 g, containing 0.9 mmol alkyne groups), $PPh_3$ (0.142 g, 0.54 mmol), $Pd(OAc)_2$ (20 mg, 0.09 mmol), $CH_2Cl_2$ (5 mL) and MeOH (0.5 mL) were combined in a test tube under $N_2$ protection. Then one drop of MSA (ca. 0.05 mL) was added into the system to start the cross-linking reaction. The mixture was stirred at room temperature overnight. Visible brown insoluble precipitates formed gradually during the reaction. At the completion of the reaction, the mixture was filtrated and the insoluble cross-linked polymer gels were washed with excessive DMF then THF to remove any residual soluble catalyst and ligand before being dried at 60 °C overnight. Yield: 0.5506 g; percentage of Pd encapsulation: 90.8%; Pd content in the heterogeneous catalyst: 1.9 wt.% or 0.18 mmol Pd/g of catalyst.

### 2.5. Synthesis of Si-ArI for 3-phase tests

A similar procedure used by Jones et al. [67] was employed for the synthesis of heterogeneous mesoporous silica-supported aryl iodide, Si-ArI. An aryl iodide-containing trimethoxysilane compound (**1** in Scheme 2) was first synthesized by reacting 4-iodoacetophenone (1.35 g, 5.5 mmol) and 3-aminopropyltrimethoxylsilane (0.895 g, 5 mmol) in 20 mL dry MeOH under reflux at 75 °C for 20 h. After being cooled to room temperature, MeOH was evaporated under reduced pressure and the product was extracted with $CH_2Cl_2$. The mixture was then concentrated and washed with cold hexane to afford **1**. Yield: 1.87 g (92%).$^1H$ NMR ($CDCl_3$): 0.78 (m, 2H, $-CH_2Si$), 1.84 [m, 4H,$-(CH_2)_2CH_2Si$], 2.07 [s, 3H, $N{=}C(Me)$], 3,34–3.52 [m, 9H, $Si(OMe)_3$], 7.44–7.63, (m, 4H, Ar*H*).

Subsequently, **1** (1.63 g, 4 mmol) was added into a toluene (20 mL) suspension of dry mesoporous silica SBA-15 (1.0 g) and the mixture was stirred at 70 °C for 24 h under $N_2$ protection. After cooling to room temperature, the mixture was filtered and the solid was washed with $CH_2Cl_2$ then hexane. After being dried under high vacuum at 80 °C overnight, the silica-supported aryl iodide (Si-ArI) was obtained as white powder. Yield: 1.258 g. Aryl iodine content (based on TGA analysis): 22 wt%.

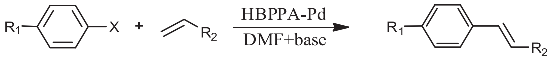
### 2.6. Mizoroki–Heck reactions catalyzed with heterogeneous Pd catalysts

A typical procedure (for run H7 in Table 2) for Mizoroki–Heck reactions of different aryl halides is as follows. The heterogeneous catalyst HBPPA-Pd-2 (0.2 mg, containing 0.036 μmol of Pd), 4'-bromoacetophenone (72 mg, 0.36 mmol), *n*-butyl acrylate (60 mg, 0.47 mmol), $K_2CO_3$ (75 mg, 0.54 mmol), and DMF (0.6 mL) were combined in a clean test tube with a magnetic stirrer. The sealed test tube was immersed into an oil bath set at 130 °C and was stirred. The conversion of the reaction was monitored with $^1H$ NMR spectroscopy. At the completion of the reaction, the insoluble salts and heterogeneous catalyst were separated from the organic solution by filtration. Water was used to wash off the inorganic salts and the catalyst was recovered.

### 2.7. Suzuki–Miyaura reactions catalyzed with HBPPA-Pd-2

A typical procedure (for run S2 in Table 3) for the Suzuki–Miyaura reactions of different aryl bromides is as follows. HBPPA-Pd-2 (0.06 mg, contain 0.011 μmol of Pd), PhBr (1.70 g, 11 mmol), PBA (1.58 g, 13 mmol), $K_2CO_3$ (2.24 g, 16 mmol), and water (18 mL) were combined in a clean test tube with a magnetic stirrer. The test tube was sealed and placed in an oil base set at 100 °C and was stirred until the reaction reached completion. During the reaction, the conversion of PhBr was monitored by

**Table 2**
Mizoroki–Heck reactions carried out with the various heterogeneous catalysts.[a]



| Run | Cat. | $R_1$ | X | $R_2$ | Pd%[b] (mol ppm) | t (h) | conv.[c] (%) | TON (×$10^3$) | TOF (×$10^3$ $h^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| H1 | HBPPA-Pd-1 | H | I | $CO_2Bu$ | 100 | 5 | >99 | 10 | 2 |
| H2 | HBPPA-Pd-2 | H | I | $CO_2Bu$ | 100 | 4 | >99 | 10 | 2.5 |
| H3 | HBPPA-Pd-3 | H | I | $CO_2Bu$ | 100 | 6 | >99 | 10 | 1.7 |
| H4 | HBPPA-Pd-4 | H | I | $CO_2Bu$ | 100 | 24 | 94 | 9.4 | 0.4 |
| H5 | HBPPA-Pd-5 | H | I | $CO_2Bu$ | 100 | 20 | >99 | 10 | 0.5 |
| H6 | HBPPA-Pd-2 | H | I | $CO_2Bu$ | 10 | 48 | 86 | 86 | 1.8 |
| H7 | HBPPA-Pd-2 | COMe | Br | $CO_2Bu$ | 100 | 20 | >99 | 10 | 0.5 |
| H8 | HBPPA-Pd-2 | COMe | Br | $CO_2Bu$ | 50 | 24 | 93 | 19 | 0.8 |
| H9 | HBPPA-Pd-2 | COMe | Br | St | 100 | 24 | 94 | 9.4 | 0.4 |
| H10 | HBPPA-Pd-2 | CN | Br | $CO_2Bu$ | 100 | 20 | >99 | 10 | 0.5 |
| H11 | HBPPA-Pd-2 | H | Br | $CO_2Bu$ | 100 | 24 | >99 | 10 | 0.4 |
| H12 | HBPPA-Pd-2 | Me | Br | $CO_2Bu$ | 100 | 24 | 23 | 2.3 | 0.1 |
| H13 | HBPPA-Pd-2 | OMe | Br | $CO_2Bu$ | 100 | 24 | 17 | 1.7 | 0.07 |

[a] Other reaction conditions: [ArX]:[alkene]:[base] = 1:1.3:1.5; [ArX] = 0.6 mmol/mL, DMF (4 mL) as the solvent for all reactions; in the reactions between PhI and BA (H1–H6), $Et_3N$ was the base and reaction temperature was 100 °C; in the reactions (H7–H13) with aryl bomides, $K_2CO_3$ was the base and reaction temperature was 130 °C.

[b] Pd molar loading relative to ArX.

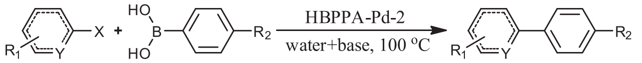
[c] Conversion of ArX determined with $^1H$ NMR spectroscopy.

$^1H$ NMR spectroscopy. At the completion of the reaction, the mixture was cooled down to room temperature and washed with ethyl acetate 3 times (2 mL × 3). The insoluble heterogeneous catalyst was recovered by filtration.

As for the Suzuki–Miyaura reactions with heteroaryl halides, the following is a typical procedure (for S16 in Table 3). 2-Bromopyridine (0.095 g, 0.6 mmol), PBA (0.088 g, 0.72 mmol), HBPPA-Pd-2 (16.5 mg, contain 3 μmol of Pd), $K_3PO_4$ (0.191 g, 0.9 mmol), and water/ethanol mixture (v/v = 2:1, 1 mL) were combined in a clean test tube having a magnetic stirring bar. The test tube was sealed and placed in an oil bath set at 100 °C. At the completion of the reaction, the mixture was cooled to room temperature and washed with ethyl acetate/water 3 times to extract the organic product.

A typical procedure (for run S18 in Table 3) for the Suzuki–Miyaura reactions of PBA with various aryl chlorides is as follows. HBPPA-Pd-2 (3.3 mg, contain 0.6 μmol of Pd), PBA (0.088 g, 0.72 mmol), CsF (0.137 g, 0.9 mmol), and water (1.5 mL)

**Table 3**
Suzuki–Miyaura reactions catalyzed with HBPPA-Pd-2.[a]



| Run | $R_1$ | X | $R_2$ | Pd%[b] (mol ppm) | t (h) | conv.[c] (%) | TON (×$10^3$) | TOF (×$10^3$ $h^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| S1 | H | Br | H | 10 | 4 | >99 | 100 | 25 |
| S2 | H | Br | H | 1 | 10 | >99 | 1000 | 100 |
| S3 | H | Br | H | 0.3 | 17 | 96 | 3200 | 187 |
| S4 | 4-COMe | Br | H | 10 | 1 | >99 | 100 | 100 |
| S5 | 4-CN | Br | H | 10 | 1 | >99 | 100 | 100 |
| S6 | 4-Me | Br | H | 10 | 8 | >99 | 100 | 13 |
| S7 | 3-Me | Br | H | 10 | 8 | >99 | 100 | 13 |
| S8 | 2-Me | Br | H | 10 | 10 | 90 | 90 | 9 |
| S9 | 4-OMe | Br | H | 10 | 8 | 95 | 95 | 12 |
| S10 | 1-bromonaphthalene[d] | Br | H | 50 | 8 | 93 | 47 | 5.8 |
| S11 | 2-bromomesitylene[e] | Br | H | 50 | 24 | 85 | 43 | 1.8 |
| S12 | H | Br | OMe | 10 | 4 | >99 | 100 | 25 |
| S13 | H | Br | COMe | 10 | 4 | >99 | 100 | 25 |
| S14 | 4-Me | Br | OMe | 10 | 6 | 88 | 88 | 15 |
| S15 | 4-Me | Br | COMe | 10 | 8 | >99 | 100 | 13 |
| S16 | 2-bromopyridine[f] | Br | H | 5000 | 24 | 96 | 0.19 | 0.01 |
| S17 | 2-bromothianaphthene[g] | Br | H | 5000 | 20 | >99 | 0.2 | 0.01 |
| S18 | 4-COMe | Cl | H | 1000 | 8 | >99 | 1 | 0.13 |
| S19 | CN | Cl | H | 1000 | 8 | >99 | 1 | 0.13 |
| S20 | H | Cl | H | 1000 | 20 | >99 | 1 | 0.05 |
| S21 | 4-Me | Cl | H | 1000 | 24 | >99 | 1 | 0.04 |
| S22 | 4-OMe | Cl | H | 1000 | 28 | >99 | 1 | 0.04 |

[a] Other reaction conditions: [ArX]:[R2-PBA]:[base] = 1: 1.3: 1.5; $T$ = 100 °C; in the reactions with ArBrs (S1–S15), [ArBr] = 0.6 mmol/mL, $K_2CO_3$ was the base and water was the solvent; in the reactions with heteroaryl bromides (S16 and S17), [ArBr] = 0.6 mmol/mL, $K_3PO_4$ was the base and water/ethanol (v/v = 2:1) was the solvent; in the reactions with ArCls (S18–22), [ArCl] = 0.4 mol/L, CsF was the base, water was the solvent along with TBAB as phase transfer agent at [TBAB]:[ArX] = 1:1.

[b] Pd molar loading relative to ArX.

[c] Conversion of ArX determined with $^1H$ NMR spectroscopy.

[d] 1-Bromonaphthalene was used as the reactant.

[e] 2-Bromomesitylene was used as the reactant.

[f] 2-Bromopyridine was used as the reactant.

[g] 2-Bromothianaphthene was used as the reactant.

were combined in a clean test tube with a magnetic stirrer. The mixture was heated in an oil bath set at 100 °C until the solids were dissolved. Then 4′-chloroacetophenone (93 mg, 0.6 mmol) and tetra-*n*-butylammonium bromide (0.19 g, 0.6 mmol) were added to the system. The test tube was sealed and placed in the oil base at 100 °C. The reaction was monitored by $^1$H NMR spectroscopy. At the completion of the reaction, the mixture was cooled down to room temperature and diluted with ethyl acetate (1 mL) and water (4 mL). The insoluble heterogeneous catalyst was recovered by filtration.

### 2.8. Allylic arylation reactions catalyzed with HBPPA-Pd-2

A typical procedure (for run A4 in Table 4) for the allylic arylation reactions is as follows. HBPPA-Pd-2 (0.15 mg, containing 0.027 μmol of Pd), cinnamyl acetate (95.2 mg, 0.54 mmol), PBA (85.5 mg, 0.7 mmol), KF (47.1 mg, 0.81 mmol), DMF (0.5 mL) and water (0.5 mL) were combined in a clean test tube with a magnetic stirrer. The sealed test tube was placed in an oil bath set at 100 °C and was stirred for a predetermined reaction time. The conversion of acetate was monitored with $^1$H NMR spectroscopy. After the reaction, the heterogeneous catalyst was recovered by filtration.

### 2.9. Reusability test

The reusability of HBPPA-Pd-2 in the Suzuki–Miyaura reaction between PhBr and PBA was carried out at the higher Pd loading of 0.1 mol% relative to PhBr. The procedure is as follows. HBPPA-Pd-2 (16.5 mg, containing 3 μmol of Pd), PhBr (0.47 g, 3 mmol), PBA (0.44 g, 3.6 mmol), $K_2CO_3$ (0.62 g, 4.5 mmol) and water (5 mL) were combined in a clean test tube with a magnetic stirrer. The tube was then sealed and the mixture was stirred at 100 °C for 3 h. The conversion of PhBr was determined with $^1$H NMR spectroscopy. At the completion of the reaction, the heterogeneous catalyst was separated from the reaction mixture by filtration. While the filtrate was characterized with atomic absorption spectroscopy, the heterogeneous catalyst was washed with acetone for 4 times (10 mL × 4) and was used to catalyze the next cycle of reaction following drying.

### 2.10. Hot filtration test

In the hot filtration test, two Suzuki–Miyaura reactions (a control run and a hot filtration run) were simultaneously carried out under exactly the same conditions. Each of two test tubes was charged with HBPPA-Pd-2 (16.5 mg, containing 3 μmol of Pd), PhBr (0.47 g, 3 mmol), PBA (0.44 g, 3.6 mmol), $K_2CO_3$ (0.62 g, 4.5 mmol), and water (5 mL). The two test tubes were then sealed and heated at 100 °C to start the reaction. The conversion of both reactions was monitored with $^1$H NMR spectroscopy. The control run did not involve hot filtration and was terminated after PhBr conversion reached 100%. For the other run involving hot filtration, the reaction mixture was quickly filtered with a syringe filter after 0.5 h of reaction (PhBr conversion: 71%) to remove the heterogeneous catalyst. The filtrate was immediately injected into another clean test tube, which was stirred at 100 °C for 40 h with the conversion of PhBr monitored with $^1$H NMR spectroscopy.

### 2.11. 3-Phase tests

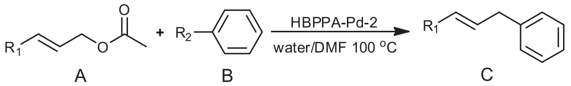
3-Phase tests using immobilized aryl halide Si-ArI were performed for Mizoroki–Heck reaction. All the liquid reagents and solvents involved were dried with 4 Å molecular sieves before use to avoid possible hydrolysis of Si-ArI. In the typical reaction, 4-iodoacetophenone (0.295 g, 1.2 mmol), *n*-butyl acrylate (0.2 g, 1.6 mmol), $Et_3N$ (0.18 g, 1.8 mmol), Si-ArI (0.15 g, containing ca. 0.12 mmol ArI), HBPPA-Pd-2 (6.7 mg, containing 1.2 μmol of Pd) and DMF (2 mL) were combined in a clean test tube having a magnetic stirring bar. The test tube was sealed and placed in an oil bath set at 100 °C. After a pre-determined reaction time, the catalyst was picked out and the insoluble Si-ArR was recovered by filtration and washed with large amount of dry DMF/THF to remove all the soluble small molecules. Subsequently, Si-ArR was hydrolyzed with 1 mol/L HCl solution overnight and extracted by $CH_2Cl_2$ (2 mL × 3 times). The solvent was then removed and the resulting compound **2** by hydrolysis (see Scheme 2) was characterized by NMR.

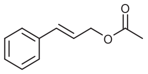
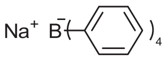
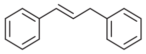
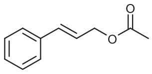
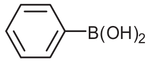
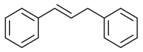
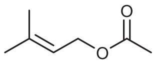
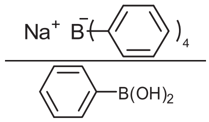
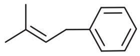
## 3. Results and discussion

### 3.1. Synthesis of heterogeneous Pd catalysts by catalytic cross-linking of HBPPA

Our concept for the synthesis of the heterogeneous Pd catalysts benefits from the unique dual capability of Pd-based catalysts in catalyzing both alkyne polymerization/oligomerization and cross-coupling reactions [64]. We employ a hyperbranched

**Table 4**
Allylic arylation reactions catalyzed with HBPPA-Pd-2[a].



| Run | A | B | Pd% (mol ppm) | C | Time (h) | Conv.[b] (%) | TON (×10$^3$) | TOF (×10$^3$ h$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| A1 |  |  | 50 |  | 6 | >99 | 20 | 3.3 |
| A2 | | | 10 | | 24 | >99 | 100 | 4.2 |
| A3 | | | 1 | | 48 | 64 | 640 | 13 |
| A4 |  |  | 50 |  | 8 | >99 | 20 | 2.5 |
| A5 | | | 10 | | 24 | >99 | 100 | 4.2 |
| A6 |  |  | 50 |  | 24 | >99 | 20 | 0.83 |
| A7 | | | 50 | | 24 | 90 | 18 | 0.75 |

[a] Other reaction conditions: for all reactions, the solvent was water/DMF mixture (v/v = 1:1; total 1 mL); T = 100 °C; [allylic acetate (A)] = 0.6 mmol/mL; for reactions with $NaBPh_4$, [A]:[$NaBPh_4$] = 1:1.3; for reactions with PBA, KF was used as base, [A]:[PBA]:[KF] = 1:1.3:1.5.

[b] Conversion of allylic acetate determined with $^1$H NMR spectroscopy.

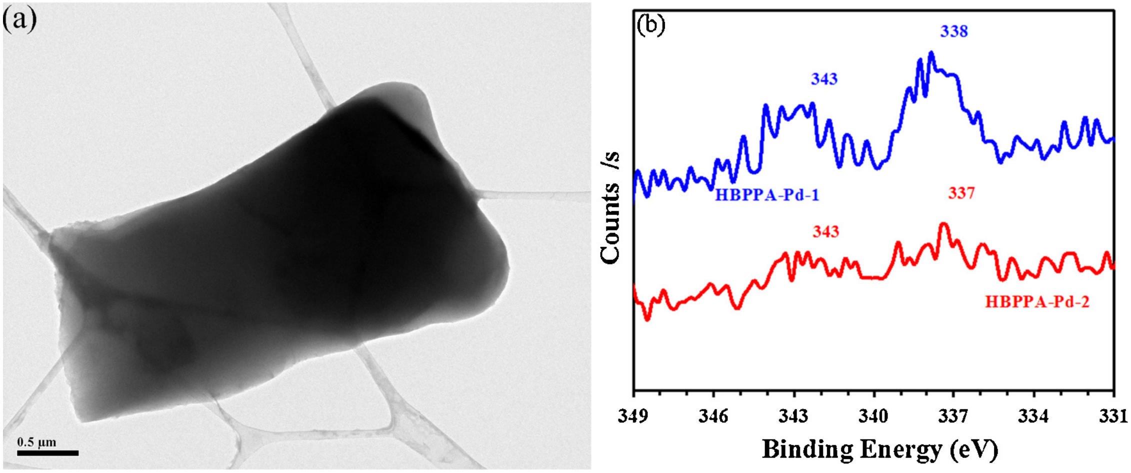
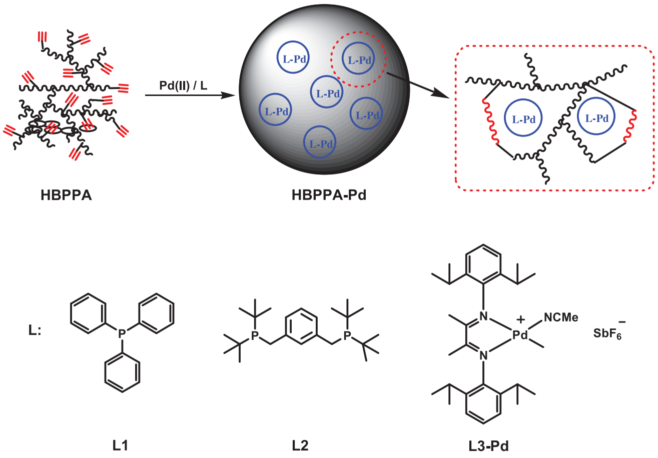


**Fig. 1.** TEM image of HBPPA-Pd-2 (a) and XPS Pd 3d spectra of HBPPA-Pd-1 and HBPPA-Pd-2 (b).

poly(phenylacetylene) (HBPPA) containing pendant alkyne groups (at a content of 1.5 mmol/g) as the cross-linkable polymer substrate to construct the heterogeneous Pd catalysts by simultaneous Pd-catalyzed cross-linking and encapsulation of the Pd species. This HBPPA was synthesized by copolymerization of phenylacetylene and 1,3-diethynylbenzene with the use of an in situ generated cationic Pd(II) catalyst system, $Pd(OAc)_2$/α,α′-bis(di-*tert*-butylphosphino)-*o*-xylene/methanesulfonic acid (MSA), a synthetic methodology developed in our earlier work [66]. The cross-linking of HBPPA is achieved herein through the polymerization/oligomerization of its pendant alkyne groups with the homogeneous cationic Pd(II) catalyst to be encapsulated [64]. During the cross-linking, the homogeneous Pd(II) catalyst, along with its ligand, is simultaneously encapsulated into the cross-linked polymer network via physical entrapment and/or coordinative binding to the pendant alkyne groups, turning itself successfully into supported ligated Pd catalyst for coupling reactions (see Scheme 1). In this way, the structure of the polymer matrix is better controlled and different ligated Pd complexes can be employed.

The catalytic performance of the ligated Pd catalysts in cross-coupling reactions is heavily related to their ligands [23]. Considering this, we have chosen to use three different homogeneous Pd(II) catalysts with varying ligands, triphenylphosphine (L1), α,α′-bis(di-*tert*-butylphosphino)-*o*-xylene (L2) as a diphosphine ligand, and a bidentate diimine ligand (L3), for the cross-linking reaction and encapsulation so as to study the effect of the ligand on catalytic performance of the resulting heterogeneous catalysts and to obtain high-performance catalysts. The two phosphine-ligated catalysts (L1-Pd and L2-Pd) were in situ generated by mixing $Pd(OAc)_2$ with the corresponding ligands (L1 or L2) in the presence of a catalytic amount of methanesulfonic acid (MSA), which generates cationic Pd(II) centers [66]. A cationic acetonitrile Pd–diimine complex (L3-Pd), a well-known ethylene polymerization catalyst [65,68–78] also shown to effectively oligomerize alkynes [79], was used as the single-component diimine-ligated catalyst. While the diphosphine-ligated catalyst L2-Pd has been well demonstrated to polymerize alkynes [66,80,81], we have found that the monophosphine-ligated catalyst L1-Pd is also highly efficient in facilitating the polymerization of phenylacetylene and 1,3-diethynylbenzene. In the case with L1-Pd, the cross-linking of HBPPA was carried out at different [alkyne]/[Pd] feed ratios (4.4:1, 8.8:1, and 26:1) while the ratio of 8.8:1 was used in those with L2-Pd and L3-Pd.



**Scheme 1.** Synthesis of heterogeneous Pd catalysts (HBPPA-Pd) containing different Pd complexes by Pd-catalyzed cross-linking of HBPPA.

The simultaneous cross-linking and catalyst encapsulation were accomplished conveniently by simply mixing and reacting HBPPA with the corresponding catalyst in solution. In all cases, successful cross-linking occurred with the gelled polymer precipitated out during the course of the reaction. At the completion of each reaction, the precipitate was thoroughly washed to remove possible non-cross-linked polymer as well as non-encapsulated Pd and ligand species, and was subsequently dried, rendering the corresponding heterogeneous supported Pd catalyst as dark or light brown particles. Table 1 lists the various heterogeneous catalysts synthesized with this strategy, along with their characterization results including yield of supported catalyst, Pd content, and percentage of Pd encapsulation.

Generally, the heterogeneous catalyst was obtained at high yield (ca. 90%) in each case except that with L2-Pd possibly because of its lower activity. With L1-Pd, increasing the [alkyne]/[Pd] feed ratio by decreasing the amount of the Pd catalyst at the fixed [alkyne] = 0.14 M leads to the increase in both yield (from 93 to 98%) and percentage of Pd encapsulation (from 75 to 97%). This indicates that the cross-linking was less efficient at the low [alkyne]/[Pd] feed ratio of 4.4 since the catalyst was at the alkyne-starved state. Comparing the three heterogeneous catalysts (HBPPA-Pd-2, HBPPA-Pd-4, and HBPPA-Pd-5) obtained at the same [alkyne]/[Pd] ratio, the percentage of Pd encapsulation increases in the order HBPPA-Pd-4 < HBPPA-Pd-5 < HBPPA-Pd-2, indicating that L1-Pd is the optimum one for quantitative encapsulation. By observation with optical microscopy, the resulting heterogeneous catalysts all have an average particle size of around 0.7 mm except HBPPA-Pd-2 whose average size is around 0.4 mm.

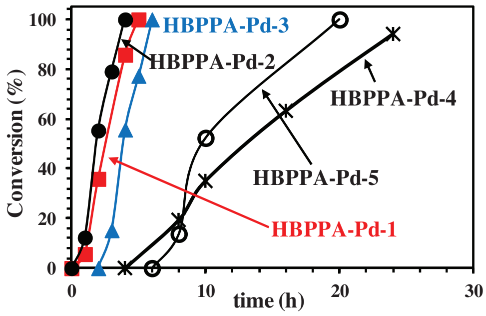


**Fig. 2.** Mizoroki–Heck reaction between PhI and BA catalyzed with various heterogeneous catalysts. Reaction conditions: [PhI] = 0.6 mol/L, [PhI]:[BA]:[$Et_3N$] = 1:1.3:1.5, Pd loading relative to PhI = 100 mol ppm, DMF as solvent at 100 °C.

The catalysts were further characterized with TEM and XPS. No Pd(0) nanoparticles were observed in HBPPA-Pd-2 under TEM, as shown in Fig. 1(a). Meanwhile, Fig. 1(b) shows the XPS Pd 3d spectra for HBPPA-Pd-1 and HBPPA-Pd-2. Given the encapsulation of the Pd species within the cross-linked polymer matrices at low contents, the XPS peaks are generally very weak despite high numbers of scans applied. For both HBPPA-Pd-1 and HBPPA-Pd-2, their Pd $3d_{3/2}$ and Pd $3d_{5/2}$ peaks center at around 343 and 338 eV, respectively. This reveals that the encapsulated Pd species are primarily Pd(II) rather than Pd(0) since Pd(II) typically has higher 3d binding energies ($3d_{5/2}$ peak typically in the range of 336–339 eV) than the Pd(0) ($3d_{5/2}$ peak typically in the range of 334.6–335.7 eV) [64,82]. Meanwhile, it also indicates the absence of the reduction of Pd(II) species during the polymerization and postpolymerization procedures.

### 3.2. *Mizoroki–Heck reactions with various heterogeneous catalysts*

The five heterogeneous Pd catalysts were first evaluated and compared for their performance in catalyzing the Mizoroki–Heck reaction between iodobenzene (PhI) and *n*-butyl acrylate (BA) at the Pd loading of 100 mol ppm relative to PhI at 100 °C under air (see runs H1–H5 in Table 2). Fig. 2 compares the conversion curves of PhI in these runs. Though quantitative conversion of PhI was obtained with all five catalysts (turn-over number, TON = 10,000), significant differences in their turn-over frequency (TOF) and conversion curves can be noted. The three heterogeneous catalysts (HBPPA-Pd-1 to HBPPA-Pd-3) synthesized with $PPh_3$-ligated L1-Pd (TOF = 2000, 2500, and 1700 $h^{-1}$, respectively) were clearly much more active with significantly shortened reaction time when compared to HBPPA-Pd-4 (TOF = 500 $h^{-1}$) and HBPPA-Pd-5 (TOF = 400 $h^{-1}$). With HBPPA-Pd-2, quantitative conversion was reached at as short as 4 h while it took 20 and 28 h with HBPPA-Pd-4 and HBPPA-Pd-5, respectively. Meanwhile, in the reactions with the latter two, a long initial induction period (ca. 6 and 4 h, respectively) with no PhI conversion was noticed (see Fig. 2).

Given their similar Pd content, the dramatic difference in the catalytic performance of these three heterogeneous catalysts reflects the significant effect of the ligand of the encapsulated Pd species on the reaction. The $PPh_3$ ligand is a commonly used classical ligand for Pd catalysts in many cross-coupling reactions [64]. Several diphosphine ligands in combination with $Pd(OAc)_2$ have been reported to efficiently catalyze the Mizoroki–Heck reactions of aryl chlorides [83–86]. Meanwhile, a range of diimine ligands in combination with $Pd(OAc)_2$ or $Pd(acetylacetonate)_2$ have also been shown to effectively facilitate both the Mizoroki–Heck and Suzuki–Miyaura reactions [87,88]. On the basis of the catalytic performance of these three heterogeneous catalysts, $PPh_3$ is far more effective than the diphosphine and diimine ligands used herein for effecting the coupling reaction.

Among the three $PPh_3$-ligated heterogeneous catalysts (HBPPA-Pd-1 to HBPPA-Pd-3), HBPPA-Pd-3 having the lowest Pd content is least active with the presence of an initial induction period of 2 h in the reaction. This is reasoned to result from its highest polymer content. Since the reactants have to diffuse through the polymer matrix to reach the catalytic Pd species for the reactions, increasing polymer content is expected to slow down the reaction due to enhanced diffusion resistance. In particular, HBPPA-1 and HBPPA-2 show similar conversion curves with HBPPA-2 being slightly more active. From this set of runs, we can conclude that $PPh_3$-ligated HBPPA-2 is the most optimum catalyst among the five heterogeneous catalysts given its catalytic performance and high efficiency in Pd encapsulation. All subsequent investigations have thus been carried out exclusively with the use of HBPPA-2.

Runs H6–H13 in Table 2 are other Mizoroki–Heck reactions carried out with HBPPA-Pd-2 using PhI and aryl bromides as the reactant. The highest TON (86,000) and TOF (1800 $h^{-1}$) were achieved in the reaction between PhI and BA (run H6) at the lowest Pd loading of 10 mol ppm. Up to date, the highest TON ($2 \times 10^6$) and TOF ($40 \times 10^3$ $h^{-1}$) values of Mizoroki–Heck reaction were recently achieved by Yamada et al. with a Si-nanowire array-stabilized Pd-nanoparticle catalyst [89]. Although lower than these values, the TON and TOF values we achieved are still among the highest reported for the Mizoroki–Heck reactions carried out with the use of heterogeneous Pd catalysts under similar conditions [14,15,64]. In the case with relatively less active aryl bromides as the reactant, the reactions were carried out at 130 °C with $K_2CO_3$ as the base. Quantitative or nearly quantitative conversions were achieved in the reactions (runs H7–11) of phenyl bromide (PhBr) or activated aryl bromides (4′-bromoacetophenone and 4-bromobenzonitrile) with BA or styrene at the Pd loading of 100 mol ppm. With deactivated aryl bromides (4-bromotoluene and 4-bromoanisole), the reactions (runs H12 and H13) were, however, much slower at the same condition. In the reactions of aryl bromides, the highest TON (19,000) and TOF (800 $h^{-1}$) were achieved with 4′-bromoacetophenone and BA as reactants at the Pd loading of 50 mol ppm. All the products from the Mizoroki–Heck reactions were featured with high *E*-selectivity with no/negligible Z-isomers observed. These results confirm that HBPPA-Pd-2 is highly effective in catalyzing the Mizoroki–Heck reactions.

### 3.3. *Suzuki–Miyaura reactions catalyzed with HBPPA-Pd-2*

Suzuki–Miyaura reactions of various aryl/heteroaryl bromides and aryl chlorides with arylboronic acids were carried out with HBPPA-Pd-2 in water as the environmentally benign solvent under air at 100 °C. Table 3 summarizes all the reactions. In the case with the relatively more active aryl bromides, reactions were performed with $K_2CO_3$ as the base without the use of any phase transfer agent. HBPPA-Pd-2 shows outstanding catalytic activity toward these reactions. In reactions employing more difficult aryl chlorides, tetra-*n*-butylammonium bromide (TBAB) was used as the phase transfer agent, along with CsF as the base, in order to enhance catalyst activity. In runs S1–S3, the reactions between PhBr and phenylboronic acid (PBA) were carried out at different Pd loadings (10, 1, 0.3 mol ppm, respectively). Quantitative conversion of PhBr was successfully achieved even in run S3 undertaken at the lowest Pd loading of 0.3 mol ppm, rendering the highest TON (3,200,000) and TOF (188,000 $h^{-1}$). To the best of our knowledge, these activity values are the highest compared to those achieved in the literature with heterogeneous Pd catalysts under similar conditions. The best results in the literature (TON = 3,570,000; TOF: 119,000 $h^{-1}$) were achieved by Uozumi et al. in the reaction between aryl iodotoluene and PBA with their self-assembled heterogeneous poly(imidazole-Pd) catalyst at the Pd loading of 0.28 mol ppm [46,47]. However, their results were achieved with the use of relatively more reactive aryl iodide in the presence a phase transfer agent that often improves catalyst activity.

At the Pd loading of 10 mol ppm, the reactions of various aryl bromides containing different substituting groups with PBA (runs S4–S9 in Table 3) were successfully accomplished with quantitative conversions achieved. The TOF values are high, ranging from about 10,000 $h^{-1}$for deactivated aryl bromides (methyl-substituted phenyl bromides and 4-bromoanisole in runs S6–S9) to 100,000 $h^{-1}$ for activated aryl bromides (4-bromobenzonitrile and 4′-bromoacetophenone in runs S4 and S5). Moreover, the reactions (S10 and S11) involving sterically hindering 1-bromonaphthalene and 2-bromomesitylene were also successfully accomplished with high conversions but at a slightly higher Pd loading of 50 mol ppm. Similarly, quantitative conversions were also achieved in the reactions of aryl bromides with activated or deactivated substituted phenylboronic acids (runs S12–S15) at the Pd loading of 10 mol ppm.

We subsequently investigated the performance of HBPPA-Pd-2 in the heteroaryl bromide-involving Suzuki–Miyaura reactions, which are of vital importance in medicinal/agrochemical fields [90]. There are quite a few homogeneous Pd catalysts reported to be capable of catalyzing versatile Suzuki–Miyaura reactions of heteroaryl compounds with high Pd loadings (1 mol% or even higher) [91–101]. However, only very limited heterogeneous Pd catalysts have been developed for such reactions [53,64,102–106]. Herein, we have found that HBPPA-Pd-2 is also efficient in catalyzing the reactions of representative heteroaryl bromide (2-bromopyridine and 3-bromothianaphthene) with PBA. Due to the lower activity of such compounds, a much higher Pd loading of 5000 ppm was, however, needed, and the solvent was also changed to ethanol/water mixture with $K_3PO_4$ as the base. As shown in Table 3 (S16 and S17), quantitative or nearly quantitative conversions were achieved in such reactions, resulting a TON around 200 and TOF around 10 $h^{-1}$. This result ranks HBPPA-Pd within the very limited heterogeneous Pd catalysts that have been reported to facilitate Suzuki–Miyaura reactions of heteroaryl compounds [53,64,102–106].

Compared to aryl iodides and bromides, aryl chlorides are much more difficult to activate in cross-coupling reactions but highly desired due to their abundance and low cost. The coupling reactions of aryl chlorides with the use of heterogeneous catalysts are often challenging [107]. We find that HBPPA-Pd-2 is effective in catalyzing the reactions of various aryl chlorides with PBA at the Pd loading of 1000 mol ppm (see runs S18–S22). The highest TOF value of 130 $h^{-1}$ was achieved with the activated aryl chlorides (4-chlorobenzonitrile and 4′-chloroacetophenone in runs S18 and S19). All these results confirm that HBPPA-Pd-2 is highly active in catalyzing the Suzuki–Miyaura reactions.

### 3.4. Allylic arylation reactions catalyzed with HBPPA-Pd-2

We have further investigated the performance of HBPPA-Pd-2 in catalyzing the allylic arylation reactions. Compared to aryl-aryl coupling, allylic arylation (i.e., allyl-aryl coupling) is less studied yet more challenging and often requires a large amount (1–10 mol%) of catalyst [108–112], except few heterogeneous catalysts that can catalyze allylic arylation at ppm level of Pd [46,47,64]. Herein, the allylic-arylation reactions between two typical allylic acetates (cinnamyl acetate, CA, and prenyl acetate, PrA) and tetraphenylborate ($NaBPh_4$)/PBA were carried out with HBPPA-Pd-2 in water/DMF mixture at 100 °C under air. Table 4 summarizes these reactions. In the reactions (runs A1–A5) between CA and $NaBPh_4$/PBA, quantitative conversions of CA were reached at the low Pd loadings of 10 and 50 mol ppm. At the further reduced Pd loading of 1 mol ppm (run A3), the reaction between CA and $NaBPh_4$ still proceeded with a CA conversion of 64% reached after 48 h of reaction, giving high TON (640,000) and TOF (13,000 $h^{-1}$) values. In the reactions with less reactive PrA (runs A6 and A7), quantitative conversions were reached within 24 h at the Pd loading of 50 mol ppm. These reactions thus confirm the high performance of HBPPA-Pd-2 in facilitating the allylic arylation reactions.

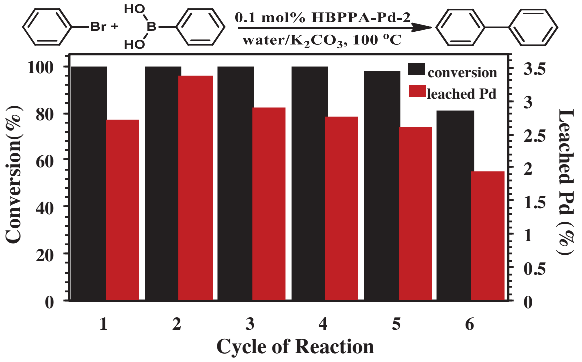
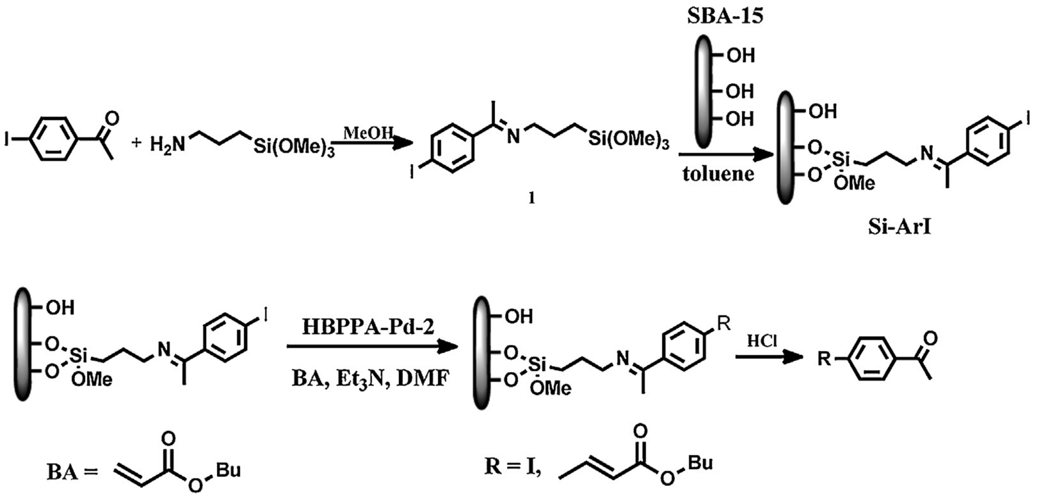


**Fig. 3.** PhBr conversion and percentage of leached Pd in the reusability test of HBPPA-Pd-2 in the Suzuki–Miyaura reaction between PhBr and PBA. Other reaction conditions: [PhBr] = 0.6 mol/L, [PhBr]:[PBA]:[$K_2CO_3$] = 1:1.3:1.5, Pd loading relative to PhBr = 0.1 mol%.

### 3.5. Reusability of HBPPA-Pd and Pd leaching during cross-coupling reactions

Relative to the homogeneous catalysts, heterogeneous catalysts show the advantage in their easy recovery and reusability. To confirm the reusability of HBPPA-Pd-2 as a reusable heterogeneous catalyst, we carried out a six-cycle reusability test of HBPPA-Pd-2 in the Suzuki–Miyaura reaction between PhBr and PBA at the high Pd loading of 1000 mol ppm at 100 °C. After the first cycle of reaction, the same catalyst was recovered and reused for additional 5 times. Each cycle of reaction lasted for 3 h. At the end of each cycle of reaction, the heterogeneous catalyst was recovered easily through filtration, washed, and dried before being used for next cycle of reaction. The reaction solution in each cycle was collected and analyzed for the conversion of PhBr and the concentration of leached Pd species. Fig. 3 summarizes the conversion of PhBr and the percentage of leached Pd species in each cycle. Quantitative conversion was maintained in the first 4 cycles of reaction, but the conversion dropped slightly to 81% in the 6th cycle of reaction. From AA measurements, the filtered reaction solution in each cycle contained leached Pd species at a concentration of around 2 mg/L (i.e., 2 ppm), indicating that about 2.8% of encapsulated Pd leached out during the reaction (see Fig. 3). In all 6 cycles of reactions, the total percentage of leached Pd is about 16.3%, which should still be considered low. Overall, this test indicates that the heterogeneous catalyst has good reusability and stability.

Given the presence of low but appreciable Pd leaching, we further carried out a hot filtration test to investigate the catalytic mechanism. In many heterogeneous catalyst systems with significant catalyst leaching, it has been found that the leached-out homogeneous Pd species present in the solution are the ones effecting the coupling reactions instead of the heterogeneous Pd species [39,67,113–116]. In the test, the reaction solution of PhBr and PBA with HBPPA-Pd-2 at the Pd loading of 1000 mol ppm was hot filtered after 0.5 h of reaction at 100 °C (PhBr conversion = 71%). The filtered solution was continued for the reaction at 100 °C. There is negligible increase of PhBr conversion in the filtered solution during the first 8 h (from 71% to 72%). Then the conversion of PhBr showed a gradual increase to 81% after 20 h and remained unchanged afterward despite being extended for another 20 h. On the opposite, the



**Scheme 2.** Synthesis of heterogeneous Si-ArI and its possible reaction in 3-phase test.

control run undertaken at identical conditions but without involving hot filtration was completed within 1 h of reaction with no induction period observed. See Fig. 4 for a comparison of their conversion curves. From this hot filtration test, it can be concluded that the leached-out homogeneous Pd species still have some activity, but considering the long induction period and the slow reaction speed compared with the heterogeneous catalyst, they have only small negligible contributions toward the reaction and the heterogeneous encapsulated Pd species play the key role [39,67,113–116].

Besides the hot-filtration test, the 3-phase test, which entails anchoring one of the reactants onto a solid support, is an alternative important technique in the determination of heterogeneity in cross-coupling reactions facilitated with solid-supported Pd catalysts [67,113,116–118]. If the cross-coupling reactivity results completely from the heterogeneous Pd species embedded in the solid support, no transformation should be observed with the anchored reactant. On the other hand, if the leached homogeneous Pd species have some activity, the anchored reactant will be converted to some degree. As shown in Scheme 2, we designed a 3-phase test for the Mizoroki–Heck reaction in organic solvent, with the use of a mesoporous silica-supported aryl iodide (Si-ArI) as a part of the aryl halide [64]. In addition, 4-iodoacetophenone (COMePhI), which has similar reactivity relative to the heterogeneous counterpart, was used as the homogeneous aryl halide (Si-ArI:COMePhI = 0.1). Similar to the hot-filtration test, the reaction was also undertaken at very high Pd loading (1000 mol ppm relative to COMePhI).

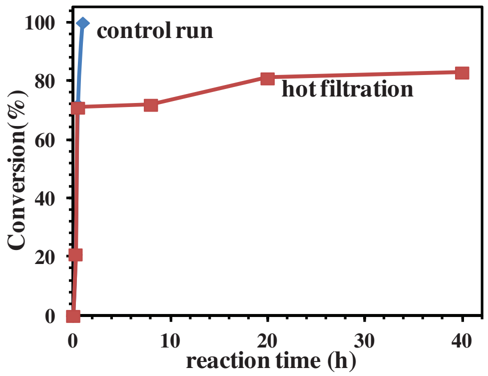


**Fig. 4.** Conversion curves of the Suzuki–Miyaura reaction between PhBr and PBA involving hot filtration and the control run without hot filtration. Reaction conditions: [PhBr] = 0.6 mol/L, [PhBr]:[PBA]:[$K_2CO_3$] = 1:1.3:1.5, Pd loading relative to [PhBr] = 0.1 mol%, water as solvent at 100 °C.

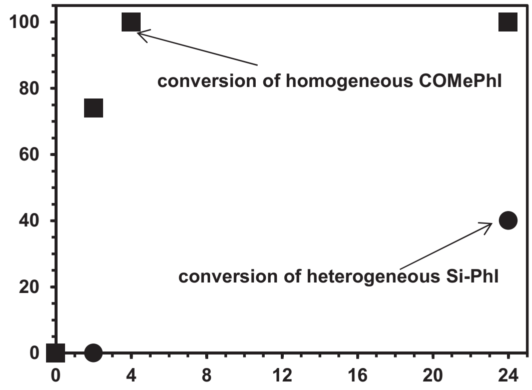


**Fig. 5.** Conversion plots of homogeneous (COMePhI) and heterogeneous (Si-PhI) aryl iodides in the 3-phase test. Reaction conditions: [ArI] = 0.6 mol/L, [ArI]:[BA]:[$Et_3N$] = 1:1.3:1.5, Pd loading relative to [ArI] = 0.1 mol%, DMF as solvent at 100 °C.

As shown in Fig. 5, no appreciable transformation of heterogeneous aryl iodide was achieved after 2 h of reaction, whereas the conversion the homogeneous COMePhI reached a high conversion of 70%. Subsequently, the homogeneous aryl iodide was quantitatively converted in 4 h. But even after extended reaction time of 24 h, the conversion of heterogeneous Si-PhI is only 40%. Considering that most cross-coupling reactions in this work were performed at Pd loadings less than 1000 mol ppm and the reaction time were around or less than 24 h, the 3-phase test further supports that HBPPA-Pd-2 catalyst is a heterogeneous catalyst and the leached homogeneous Pd species only have a small contribution compared to the immobilized Pd species. This differentiates HBPPA-Pd-2 catalyst from many other reported heterogeneous Pd catalysts where the leached homogeneous Pd species are in fact the true ones responsible for the reactions [39,67,113–118].

## 4. Conclusions

We have demonstrated in this work the synthesis of heterogeneous Pd catalysts for coupling reactions with the use of a HBPPA containing pendant alkyne groups as the cross-linkable polymer substrate via one-step encapsulation of the Pd species that catalyze the cross-linking reactions. The in situ generated triphenylphosphine-ligated Pd(II) catalyst (L2-Pd) has been identified to be the most optimum one for effecting the cross-linking and encapsulation. We have found that HBPPA-Pd-2 is efficient and highly active in facilitating the Mizoroki–Heck, Suzuki–Miyaura, and allylic arylation reactions with the relative molar Pd loading at ppm levels. A high TON of 86,000 and a high TOF of 1800 $h^{-1}$ have been achieved in the Mizoroki–Heck reaction between PhI and BA with HBPPA-Pd-2 at the low Pd loading of 10 mol ppm. More notably, HBPPA-Pd-2 showed very high activity in Suzuki–Miyaura reactions with various aryl/heteroaryl bromides (Pd loading down to 10 mol ppm with TON up to 100,000 and TOF up to 100,000 $h^{-1}$) and low-reactivity aryl chlorides (at the Pd loading of 1000 mol ppm with TON = 1000 and TOF up to 130 $h^{-1}$). In particular, the reaction between PhBr and PBA occurred quantitatively even at a very low Pd loading of 0.3 ppm, rendering very high TON (3200,000) and TOF (188,000 $h^{-1}$) values that are comparable to or even better than the best values reported in the literature. The allylic arylation reactions were also successfully accomplished with HBPPA-Pd-2 at the Pd loading of as low as 1 mol ppm (TON up to 640,000 and TOF up to 13,000 $h^{-1}$). The 6-cycle reusability test of HBPPA-Pd-2 in the Suzuki–Miyaura reaction between PhBr and PBA has confirmed that the heterogeneous catalyst is easily recyclable and reusable with well-retained catalytic activity and low Pd leaching. A hot filtration test, together with a 3-phase test, has also verified that the catalyst is truly a heterogeneous one with negligible contributions from the leached homogeneous Pd species toward the catalytic activity. The heterogeneous catalyst synthesized through this unique simultaneous cross-linking and encapsulation strategy thus has the good potential for applications in carbon–carbon cross-coupling reactions.

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## References

[1] A. de Meijere, F. Diederich (Eds.), Metal-Catalyzed Cross-Coupling Reactions, vol. 2, 2nd ed., Wiley-VCH, Weinheim, 2004.
[2] E. Negishi, A. de Meijere (Eds.), Handbook of Organopalladium Chemistry for Organic Synthesis, vol. 2, Wiley, New York, 2002.
[3] C.C.C.J. Seechurn, M.O. Kitching, T.J. Colacot, V. Snieckus, Angew. Chem. Int. Ed. 51 (2012) 5062–5085.
[4] N. Miyaura, A. Suzuki, J. Chem. Soc. Chem. Commun. (1979) 866–867.
[5] N. Miyaura, A. Suzuki, Chem. Rev. 95 (1995) 2457–2483.
[6] A. Suzuki, J. Organomet. Chem. 576 (1999) 147–168.
[7] N. Miyaura, Top. Curr. Chem. 219 (2002) 11–59.
[8] R.F. Heck, J.P. Nolley, J. Org. Chem. 37 (1972) 2320–2322.
[9] T. Mizoroki, K. Mori, A. Ozaki, Bull. Chem. Soc. Jpn. 44 (1971) 581.
[10] R.F. Heck, Org. React. 27 (1982) 345–390.
[11] A. de Meijere, F.E. Meyer, Angew. Chem. Int. Ed. 33 (1995) 2379–2411.
[12] I.P. Beletskaya, A.V. Cheprakov, Chem. Rev. 100 (2000) 3009–3066.
[13] M. Oestreich, The Mizoroki–Heck Reaction, Wiley, Chichester, UK, 2009.
[14] A. Molnár, Chem. Rev. 111 (2011) 2251–2320.
[15] L. Yin, J. Liebscher, Chem. Rev. 107 (2007) 133–173.
[16] Y. Uozumi, Top. Curr. Chem. 242 (2004) 77–112.
[17] R. Akiyama, S. Kobayashi, Chem. Rev. 109 (2009) 594–642.
[18] S. Kobayashi, H. Miyamura, Aldrichim. Acta 46 (2013) 3–19.
[19] A.C. Albéniz, N. Carrera, Eur. J. Inorg. Chem. 2011 (2011) 2347–2360.
[20] A. Balanta, C. Godard, C. Claver, Chem. Soc. Rev. 40 (2011) 4973–4985.
[21] V. Polshettiwar, C. Len, A. Fihri, Coord. Chem. Rev. 253 (2009) 2599–2626.
[22] M. Pagliaro, V. Pandarus, R. Ciriminna, F. Béland, P.D. Carà, Chemcatchem 4 (2012) 432–445.
[23] V. Farina, Adv. Synth. Catal. 346 (2004) 1553–1582.
[24] D.E. Bergbreiter, Chem. Rev. 102 (2002) 3345–3384.
[25] D.E. Bergbreiter, J. Tian, C. Hongfa, Chem. Rev. 109 (2009) 530–582.
[26] J. Lu, P.H. Toy, Chem. Rev. 109 (2009) 815–838.
[27] T.J. Dickerson, N.N. Reed, K.D. Janda, Chem. Rev. 102 (2002) 3325–3344.
[28] R. van de Coevering, R.J.M. Klein Gebbink, G. van Koten, Prog. Polym. Sci. 30 (2005) 474–490.
[29] D. Astruc, F. Chardac, Chem. Rev. 101 (2001) 2991–3023.
[30] R.M. Crooks, M. Zhao, L. Sun, V. Chechik, L.K. Yeung, Acc. Chem. Res. 34 (2000) 181–190.
[31] R. van Heerbeek, P.C.J. Kamer, P.W.N.M. van Leeuwen, J.N.H. Reek, Chem. Rev. 102 (2002) 3717–3756.
[32] R. Sablong, U. Schlotterbeck, D. Vogt, S. Mecking, Adv. Synth. Catal. 345 (2003) 333–336.
[33] P. Liu, Z. Ye, W.-J. Wang, B.-G. Li, Macromolecules 46 (2013) 72–82.
[34] S. Ikegami, H. Hamamoto, Chem. Rev. 109 (2009) 583–593.
[35] R. Akiyama, S. Kobayashi, Angew. Chem. Int. Ed. 40 (2001) 3469–3471.
[36] R. Akiyama, S. Kobayashi, J. Am. Chem. Soc. 125 (2003) 3412–3413.
[37] K. Okamoto, R. Akiyama, H. Yoshida, T. Yoshida, S. Kobayashi, J. Am. Chem. Soc. 127 (2005) 2125–2135.
[38] A. Biffis, N. Orlandi, B. Corain, Adv. Mater. 15 (2003) 1551–1555.
[39] A.M. Caporusso, P. Innocenti, L.A. Aronica, G. Vitulli, R. Gallina, A. Biffis, M. Zecca, B. Corain, J. Catal. 234 (2005) 1–13.
[40] Y. Uozumi, R. Nakao, Angew. Chem. Int. Ed. 42 (2003) 194–197.
[41] J.K. Cho, R. Najman, T.W. Dean, O. Ichihara, C. Muller, M. Bradley, J. Am. Chem. Soc. 128 (2006) 6276–6277.
[42] K. Glegola, E. Framery, K.M. Pietrusiewicz, D. Sinou, Adv. Synth. Catal. 348 (2006) 1728–1733.
[43] S. Ogasawara, S. Kato, J. Am. Chem. Soc. 132 (2010) 4608–4613.
[44] C. Ramaro, S.V. Ley, S.C. Smith, I.M. Shirley, N. DeAlmeida, Chem. Commun. (2002) 1132–1133.
[45] S.V. Ley, C. Ramarao, R.S. Gordon, A.B. Holmes, A.J. Morrison, I.F. McConvey, I.M. Shirley, S.C. Smith, M.D. Smith, Chem. Commun. (2002) 1134–1135.
[46] S.M. Sarkar, Y. Uozumi, Y.M.A. Yamada, Angew. Chem. Int. Ed. 50 (2011) 9437–9441.
[47] Y.M.A. Yamada, S.M. Sarkar, Y. Uozumi, J. Am. Chem. Soc. 134 (2012) 3190–3198.
[48] P. Liu, Z. Dong, Z. Ye, W.-J. Wang, B.-G. Li, J. Mater. Chem. A 1 (2013) 15469–15478.
[49] T. Hasell, C.D. Wood, R. Clowes, J.T.A. Jones, Y.Z. Khimyak, D.J. Adams, A.I. Cooper, Chem. Mater. 22 (2010) 557–564.
[50] P. Zhang, Z. Weng, J. Guo, C. Wang, Chem. Mater. 23 (2011) 5243–5249.
[51] B. Li, Z. Guan, W. Wang, X. Yang, J. Hu, B. Tan, T. Li, Adv. Mater. 24 (2012) 3390–3395.
[52] K.E. Price, D.T. McQuade, Chem. Commun. (2005) 1714–1716.
[53] K. Inada, N. Miyaura, Tetrahedron 56 (2000) 8661–8664.
[54] E. Groppo, W. Liu, O. Zavorotynska, G. Agostini, G. Spoto, S. Bordiga, C. Lamberti, A. Zecchina, Chem. Mater. 22 (2010) 2297–2308.
[55] S. Schweizer, J.-M. Becht, C. Le Drian, Org. Lett. 9 (2007) 3777–3780.
[56] F. Wen, W. Zhang, G. Wei, Y. Wang, J. Zhang, M. Zhang, L. Shi, Chem. Mater. 20 (2008) 2144–2150.
[57] Y. Yu, T. Hu, X. Chen, K. Xu, J. Zhang, J. Huang, Chem. Commun. 47 (2011) 3592–3594.
[58] G. Liu, M. Hou, J. Song, T. Jiang, H. Fan, Z. Zhang, B. Han, Green Chem. 12 (2010) 65–69.
[59] Y. Wang, J. Liu, C. Xia, Tetrahedron Lett. 52 (2011) 1587–1591.
[60] Y. Wang, J. Zhang, W. Zhang, M. Zhang, J. Org. Chem. 74 (2009) 1923–1931.
[61] K.S. Sivudu, N.M. Reddy, N.N. Prasad, K.M. Raju, Y.M. Mohan, J.S. Yadav, G. Sabitha, D. Shailaja, J. Mol. Catal. A: Chem. 295 (2008) 10–17.
[62] G. Cravotto, D. Garella, S. Tagliapietra, A. Stolle, S. Schüler, S.E.S. Leonhardt, B. Ondruschka, New J. Chem. 36 (2012) 1304–1307.
[63] K. Martina, S.E.S. Leonhardt, B. Ondruschka, M. Curini, A. Binello, G. Cravotto, J. Mol. Catal. A: Chem. 334 (2011) 60–64.
[64] Z. Dong, Z. Ye, Adv. Synth. Catal. (2014), http://dx.doi.org/10.1002/adsc.201400520 (in press).
[65] L.K. Johnson, C.M. Killian, M. Brookhart, J. Am. Chem. Soc. 117 (1995) 6414–6415.
[66] Z. Dong, Z. Ye, Macromolecules 45 (2012) 5020–5031.
[67] K. Yu, W. Sommer, M. Weck, C.W. Jones, J. Catal. 226 (2004) 101–110.
[68] Z. Ye, L. Xu, Z. Dong, P. Xiang, Chem. Commun. 49 (2013) 6235–6255.
[69] Z. Dong, Z. Ye, Polym. Chem. 3 (2012) 286–301.
[70] Z. Ye, S. Li, Macromol. React. Eng. 4 (2010) 319–332.
[71] K. Zhang, J. Wang, R. Subramanian, Z. Ye, J. Lu, Q. Yu, Macromol. Rapid Commun. 28 (2007) 2185–2191.
[72] J. Wang, K. Zhang, Z. Ye, Macromolecules 41 (2008) 2290–2293.
[73] Y. Zhang, Z. Ye, Chem. Commun. (2008) 1178–1180.
[74] Y. Zhang, Z. Ye, Macromolecules 41 (2008) 6331–6338.
[75] Y. Xu, P. Xiang, Z. Ye, W.-J. Wang, Macromolecules 43 (2010) 8026–8038.
[76] Z. Zhang, Z. Ye, Chem. Commun. 48 (2012) 7940–7942.
[77] L. Xu, Z. Ye, Chem. Commun. 49 (2013) 8800–8802.
[78] E. Landry, Z. Ye, Macromol. Rapid Commun. 34 (2013) 1493–1498.
[79] A.M. LaPointe, M. Brookhart, Organometallics 17 (1998) 1530–1537.
[80] J. Huber, S. Mecking, Angew. Chem. Int. Ed. 45 (2006) 6314–6317.
[81] J. Huber, S. Mecking, Macromolecules 43 (2010) 8718–8723.
[82] S. MacQuarrie, B. Nohair, J.H. Hortons, S. Kaliaguine, C.M. Crudden, J. Phys. Chem. C 114 (2010) 57–64.
[83] Y. Ben-David, M. Portnoy, M. Gozin, D. Milstein, Organometallics 11 (1992) 1995–1996.
[84] M. Portnoy, Y. Ben-David, D. Milstein, Organometallics 12 (1993) 4734–4735.
[85] M. Portnoy, D. Milstein, Organometallics 12 (1993) 1665–1673.
[86] M. Portnoy, Y. Ben-David, I. Rousso, D. Milstein, Organometallics 13 (1994) 3465–3479.
[87] G.A. Grasa, A.C. Hillier, S.P. Nolan, Org. Lett. 3 (2001) 1077–1080.

[88] G.A. Grasa, R. Singh, E.D. Stevens, S.P. Nolan, J. Organomet. Chem. 687 (2003) 269–279.
[89] Y.M.A. Yamada, Y. Yuyama, T. Sato, S. Fujikawa, Y. Uozumi, Angew. Chem. Int. Ed. 53 (2014) 127–131.
[90] S. Ge, J.F. Hartwig, Angew. Chem. Int. Ed. 51 (2012) 12837–12841.
[91] G.A. Molander, B. Biolatto, J. Org. Chem. 68 (2003) 4302–4314.
[92] N. Kudo, M. Perseghini, G.C. Fu, Angew. Chem. Int. Ed. 45 (2006) 1282–1284.
[93] K.L. Billingsley, K.W. Anderson, S.L. Buchwald, Angew. Chem. Int. Ed. 45 (2006) 3484–3488.
[94] K. Billingsley, S.L. Buchwald, J. Am. Chem. Soc. 129 (2007) 3358–3366.
[95] G.A. Molander, B. Canturk, L.E. Kennedy, J. Org. Chem. 74 (2009) 973–980.
[96] T. Kinzel, Y. Zhang, S.L. Buchwald, J. Am. Chem. Soc. 132 (2010) 14073–14075.
[97] M.A. Düfert, K.L. Billingsley, S.L. Buchwald, J. Am. Chem. Soc. 135 (2013) 12877–12885.
[98] T. Noël, A.J. Musacchio, Org. Lett. 13 (2011) 5180–5183.
[99] C.A. Fleckenstein, H. Plenio, J. Org. Chem. 73 (2008) 3236–3244.
[100] A.S. Guram, A.O. King, J.G. Allen, X. Wang, L.B. Schenkel, J. Chan, E.E. Bunel, M.M. Faul, R.D. Larsen, M.J. Martinelli, P.J. Reider, Org. Lett. 8 (2006) 1787–1789.
[101] A.S. Guram, X. Wang, E.E. Bunel, M.M. Faul, R.D. Larsen, M.J. Martinelli, J. Org. Chem. 72 (2007) 5104–5112.
[102] S.-W. Kim, M. Kim, W.Y. Lee, T. Hyeon, J. Am. Chem. Soc. 124 (2002) 7642–7643.
[103] Y. Kitamura, S. Sako, T. Udzu, A. Tsutsui, T. Maegawa, Y. Monguchi, H. Sajiki, Chem. Commun. (2007) 5069–5071.
[104] Y. Kitamura, S. Sako, A. Tsutsui, Y. Monguchi, T. Maegawa, Y. Kitade, H. Sajiki, Adv. Synth. Catal. 352 (2010) 718–730.
[105] D.-H. Lee, M. Choi, B.-W. Yu, R. Ryoo, A. Taher, S. Hossain, M.-J. Jin, Adv. Synth. Catal. 351 (2009) 2912–2920.
[106] D.-H. Lee, J.-Y. Jung, M.-J. Jin, Green Chem. 12 (2010) 2024–2029.
[107] A.F. Littke, G.C. Fu, Angew. Chem. Int. Ed. 41 (2002) 4176–4211.
[108] H. Tsukamoto, M. Sato, Y. Kondo, Chem. Commun. (2004) 1200–1201.
[109] K. Manabe, K. Nakada, N. Aoyama, S. Kobayashi, Adv. Synth. Catal. 347 (2005) 1499–1503.
[110] H. Ohmiya, Y. Makida, D. Li, M. Tanabe, M. Sawamura, J. Am. Chem. Soc. 132 (2010) 879–889.
[111] H. Ohmiya, Y. Makida, T. Tanaka, M. Sawamura, J. Am. Chem. Soc. 130 (2008) 17276–17277.
[112] Y. Uozumi, H. Danjo, T. Hayashi, J. Org. Chem. 64 (1999) 3384–3388.
[113] N.T.S. Phan, M. Van Der Sluys, C.W. Jones, Adv. Synth. Catal. 348 (2006) 609–679.
[114] F. Zhao, B.M. Bhanage, M. Shirai, M. Arai, J. Catal. 194 (2000) 479–483.
[115] K. Kohler, R.G. Heidenreich, J.G.E. Krauter, J. Pietsch, Chem. Eur. J. 8 (2002) 622–631.
[116] D.E. Bergbreiter, P.L. Osburn, J.D. Frels, Adv. Synth. Catal. 347 (2005) 172–184.
[117] I.W. Davies, L. Matty, D.L. Hughes, P.J. Reider, J. Am. Chem. Soc. 123 (2001) 10139–10140.
[118] S.J. Broadwater, D.T. McQuade, J. Org. Chem. 71 (2006) 2131–2134.