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Pd(0)–polyethyleneimine complex as a partial hydrogenation catalyst of alkynes to alkenes

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ABSTRACT

We have developed a Pd(0)–polyethyleneimine [Pd(0)–PEI] complex for the selective partial hydrogenation of alkynes to the corresponding alkenes. Notably, Pd(0)–PEI catalyzed the partial hydrogenation of *mono*-substituted alkynes with an excellent selectivity (77–100%), which was very difficult to achieve even with the Lindlar catalyst. Moreover, the use of Pd(0)–PEI led to no reduction in the other reducible functionalities, such as the *N*-benzyloxycarbonyl (*N*-Cbz), benzyl ester, benzyl ether and *O*-*tert*-butyldimethylsilyl (*O*-TBS) protective groups; that is, Pd(0)–PEI offers a concise synthetic route to a variety of functionalized alkenes.

1. Introduction

The catalytic partial hydrogenation of alkynes to alkenes is an important synthetic process since alkenes are useful intermediates for the preparation of an enormous number of bioactive molecules and natural products [1–6]. The selectivity between partial hydrogenation and over-hydrogenation could be controlled by only a few catalysts such as Pdc (a Pd catalyst prepared from NaH, *t*-$C_5H_{11}OH$, and $Pd(OAc)_2$ in THF) [7], low-active Raney Ni [8–16], P-1 Ni (prepared by the $NaBH_4$ reduction of $Ni(OAc)_2$ in water) [17], or P-2 Ni (prepared by the $NaBH_4$ reduction of $Ni(OAc)_2$ in EtOH) [18–20], Nic (a Ni catalyst prepared from NaH, *t*-$C_5H_{11}OH$, and $Ni(OAc)_2$ in THF) [21,22], Au nanoparticles [23], and homogeneous Rh and Cr complexes [24,25], although these catalysts often have a pyrophoric property, narrow substrate scope, require the addition of a base, careful handling, and a low *cis*–*trans* selectivity. The Lindlar catalyst [Pd on $CaCO_3$ poisoned by $Pb(OAc)_2$] [26] is a widely used catalyst for such partial hydrogenations and has achieved the chemo- and geometrically selective partial hydrogenation in industry as well as in the laboratory to date, although the addition of harmful $Pb(OAc)_2$ and quinoline is necessary. However, the partial hydrogenation of *mono*-substituted (terminal) alkynes were hardly applied, since the overreduction to the corresponding alkanes readily occurred. Hence, the Lindlar's method is limited only to the partial hydrogenation of *di*-substituted (internal) alkynes [27]. In 1999, van Laren and Elsevier reported that a Pd complex fixed with the rigid bidentate nitrogen ligand, bis(arylimino)acenaphthene(bian), catalyzed the highly selective partial hydrogenation of alkynes to *cis*-alkenes [28]. Recently, Kobayashi and co-workers developed the phosphinated polymer incarcerated palladium catalyst (PI Pd) and used it for the partial hydrogenation [29]. Yus and co-workers reported an efficient partial hydrogenation of both internal and terminal alkynes using Ni nanoparticles, although the method required the addition of a strictly controlled amount of lithium powder [30]. In spite of such precedents, there is still a significant demand for the development of novel catalysts that can achieve an excellent selectivity for the hydrogenation of alkynes especially *mono*-substituted alkynes to the corresponding alkenes without any additives and/or pretreatments.

In 1998, we established a chemoselective hydrogenation method by the addition of nitrogen-containing bases as a catalyst poison to the reaction media [31]. Moreover, we demonstrated that the palladium on carbon–ethylenediamine complex [Pd/C(en)], of which ethylenediamine is coordinated to the Pd/C, catalyzed the chemoselective hydrogenation of such reducible functionalities as alkenes, alkynes, azides, and nitro groups, while the coexisting *O*-benzyl, *O*-triethylsilyl (*O*-TES) or *N*-benzyloxycarbonyl (*N*-Cbz) protective

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groups, benzyl alcohols or epoxides were untouched [32–38]. We also have developed a silk fibroin (Fib)-supported Pd(0) catalyst for the chemoselective hydrogenation of alkynes, alkenes, and azides in the presence of other reducible functionalities including aromatic carbonyls, benzyl esters, *N*-Cbz groups and cyano groups [39–42]. During our further study to develop a new Pd catalyst for the hydrogenation of compounds possessing a different chemoselectivity, we found that polyethyleneimine (PEI, branched polymer, average molecular weight approximately 25,000) [43], which is often safely used in stream water purification, was likely to be a good carrier of Pd(0) metal by multi-coordination bonds with polyamine functionalities which would strongly reduce the catalytic activity of Pd(0) as a catalyst poison. Although Royer and co-workers previously utilized PEI as a mold of Pd metal and prepared the Pd(0)–PEI "ghost" catalyst, it was a highly active hydrogenation catalyst and never applied to the partial hydrogenation of alkynes [44,45]. Herein, we now wish to describe the development of a general and highly chemoselective Pd(0) catalyst strongly coordinated to PEI and its application to the partial hydrogenation of various alkynes including both *mono*- and *di*-substituted alkynes to the corresponding alkenes [46,47].

2. Experimental

2.1. General

$Pd(OAc)_2$ was purchased from Kishida (catalog No. 000-59012). Polyethyleneimine (PEI, average Mw ~25,000 by light scattering (LS), average Mn ~10,000 by GPC, high molecular weight, water free) was purchased from Aldrich (catalog No. 408727). The Lindlar catalyst was purchased from Aldrich (catalog No. 205737). HPLC grade MeOH and cyclohexane and dehydrated EtOAc were purchased from Wako Pure Chemical Industries Ltd., and dehydrated 1,4-dioxane was purchased from Kanto Chemical Co. These solvents were used without purification. CH_2Cl_2 was distilled from calcium hydride. All other reagents were purchased from commercial sources and used without further purification. Flash column chromatography was performed using Silica Gel 60 N (Kanto Chemical Co., Inc., 63–210 μm spherical, neutral). The ^1H NMR and ^{13}C NMR spectra were recorded by a JEOL AL 400 spectrometer or JEOL EX 400 spectrometer (400 MHz for ^1H NMR and 100 MHz for ^{13}C NMR). The chemical shifts (δ) are expressed in ppm and are internally referenced (0.00 ppm for TMS for $CDCl_3$ for ^1H NMR and 77.0 ppm for $CDCl_3$ for ^{13}C NMR). The EI and FAB mass spectra were obtained by a JEOL JMS-SX102A instrument.

2.2. Experimental procedure for catalyst preparation (Table 1)

2.2.1. Preparation of catalyst A

PEI (2.11 g) was deaerated for 48 h *in vacuo* and MeOH (100 mL, HPLC grade) was added. After PEI was homogeneously dissolved, the resulting solution was quickly poured into a round-bottom flask that contained $Pd(OAc)_2$ (225 mg, 1.00 mmol) under an argon atmosphere. Next, the round-bottom flask was filled with argon through three vacuum/argon (balloon) cycles after the $Pd(OAc)_2$ had completely dissolved in the MeOH–PEI solution. The resulting solution was stirred at room temperature for 24 h and concentrated *in vacuo*.

2.2.2. Preparation of catalyst B

The preparation method for catalyst A was followed, except for the gas. Hydrogen was used in place of argon during the 24 h-stirring.

2.2.3. Preparation of catalyst C

PEI (1.99 g) was deaerated for 48 h *in vacuo* and MeOH (100 mL) was then added. After the PEI had homogeneously dissolved, the resulting solution was quickly poured into a round-bottom flask that contained $PdCl_2$ (177 mg, 1.00 mmol) under an argon atmosphere. Due to the poor solubility of $PdCl_2$ in the MeOH–PEI solution, the mixture was stirred at 50 °C for 30 min and then at 90 °C for 11 h. The round-bottom flask was filled with H_2 through three vacuum/H_2 (balloon) cycles, and the resulting solution was stirred at 90 °C for 24 h and then concentrated *in vacuo*.

2.2.4. Preparation of catalyst D

PEI (636 mg) was deaerated for 48 h *in vacuo*, and then MeOH (25 mL) was added. After the PEI was homogeneously dissolved, the resulting solution was quickly poured into a round-bottom flask which contained a mixture of $Pd(PPh_3)_4$ (364 mg, 0.315 mmol) and THF (5 mL) under an argon atmosphere. The round-bottom flask was filled with argon through three vacuum/argon (balloon) cycles after the $Pd(PPh_3)_4$ had completely dissolved in the MeOH–THF–PEI solution. The resulting solution was stirred at rt for 24 h and then concentrated *in vacuo*.

2.2.5. Comparison of catalyst activity using catalysts A–D

In a test tube were placed diphenylacetylene (**1**, 178 mg, 1.00 mmol), the catalyst (A, B, C, or D) (17.8 mg, 10 wt% of **1**) a stirring bar, MeOH (1 mL), and EtOAc (1 mL). The air inside the test tube was replaced with H_2 through three vacuum/H_2 (balloon) cycles, and then the mixture was vigorously stirred at ambient temperature. After 24 h, the reaction mixture was partitioned between Et_2O (10 mL) and H_2O (10 mL), and the organic layer was washed with brine (10 mL), dried ($MgSO_4$), filtered, and concentrated *in vacuo* to afford the residue composed of the diphenylacetylene (**1**), *cis*-stilbene (**2**), *trans*-stilbene (**3**), and 1,2-diphenylethane (**4**). The product ratio was determined by comparison of the intensity of the following three peaks at 6.60 ppm (olefin protons of **2**), 7.12 ppm (olefin protons of **3**) and 2.92 ppm (methylene protons of **4**) in the ^1H NMR spectrum. The structures of all compounds, **1**–**4**, were determined on the basis of the ^1H NMR spectra of authentic commercial samples.

2.3. Solvent effect on the partial hydrogenation of diphenylacetylene (*1*) using 5% Pd(0)–PEI catalyst (Table 2)

The procedure for comparison of the activity of catalysts A–D (Section 2.2.5) was followed, except for the catalyst and solvent. Catalyst B [5% Pd(0)–PEI, 17.8 mg] was used, and cyclohexane, EtOAc, 1,4-dioxane, and MeOH, which is listed in Table 2, were examined.

2.4. Time course study in the 5% Pd(0)–PEI catalyzed hydrogenation (Fig. 2)

In a test tube were placed diphenylacetylene (**1**, 178 mg, 1.00 mmol), 5% Pd(0)–PEI (17.8 mg, 10 wt% of **1**), a stirring bar, MeOH (1 mL), and 1,4-dioxane (1 mL). The air inside the test tube was replaced with H_2 through three vacuum/H_2 (balloon) cycles, and then the mixture was vigorously stirred at ambient temperature for a specific time (3, 6, 12, 24, and 48 h). The reaction mixture was partitioned between Et_2O (10 mL) and H_2O (10 mL), and the organic layer was washed with brine (10 mL), dried ($MgSO_4$), filtered, and concentrated *in vacuo* to afford the residue composed of the diphenylacetylene (**1**), *cis*-stilbene (**2**), *trans*-stilbene (**3**), and 1,2-diphenylethane (**4**). The product ratio was determined by comparison of the intensity of the three peaks at 6.60 ppm (olefin protons of **2**), 7.12 ppm (olefin protons of **3**) and 2.92 ppm (methylene protons of **4**) in the ^1H NMR spectrum. The structures of all compounds, **1**–**4**, were determined on the basis of the ^1H NMR spectra of authentic commercial samples.

2.5. Typical procedure for the Pd(0)–PEI-catalyzed partial hydrogenation of di-substituted alkynes and experimental results (Table 3)

In a test tube were placed the substrate (**5**, 1.00 mmol), 5% Pd(0)–PEI (10 wt% of substrate), a stirring bar, MeOH (1 mL), and 1,4-dioxane (1 mL). The air inside the test tube was replaced with H_2 through three vacuum/H_2 (balloon) cycles, and then the mixture was vigorously stirred at ambient temperature. After 24 h, the reaction mixture was partitioned between Et_2O (10 mL) and H_2O (10 mL), and the organic layer was washed with brine (10 mL), dried ($MgSO_4$), filtered, and concentrated *in vacuo* to afford the residue composed of the unreacted *di*-substituted alkyne (**5**), *cis*-alkene (**6**), *trans*-alkene (**7**), and over-reduced alkane (**8**) and the ratio was determined by a ^{1}H NMR analysis.

2.5.1. Ethyl cis-cinnamate and ethyl 3-phenylpropionate (Entry 1)

Obtained from ethyl phenylpropiolate (174 mg, 1.00 mmol). The ratio of ethyl *cis*-cinnamate and ethyl 3-phenylpropionate was estimated at 94:6 based on the intensity of the ^{1}H NMR signals at 5.93 ppm (olefin proton of ethyl *cis*-cinnamate) and 2.60 ppm (methylene protons of ethyl 3-phenylpropionate). The chemical shifts of ethyl *cis*-cinnamate and ethyl 3-phenylpropionate were in agreement with those of the literature [48] and commercial authentic sample, respectively.

2.5.2. cis-4-Phenyl-3-buten-2-one, trans-4-phenyl-3-buten-2-one and benzyl methyl ketone (Entry 2)

Obtained from 4-phenyl-3-butyn-2-one (144 mg, 1.00 mmol). The ratio of *cis*-4-phenyl-3-buten-2-one, *trans*-4-phenyl-3-buten-2-one and benzyl methyl ketone was estimated at 36:58:6 based on the intensity of the ^{1}H NMR signals at 6.18 ppm (olefin proton of *cis*-4-phenyl-3-buten-2-one), 6.72 ppm (olefin proton of *trans*-4-phenyl-3-buten-2-one) and 2.76 ppm (methylene protons of benzyl methyl ketone). The chemical shifts of *cis*- and *trans*-isomers and benzyl methyl ketone were in agreement with those of the literature for *cis*/*trans* isomers [49] and commercial authentic sample for benzyl methyl ketone.

2.5.3. cis-Cinnamic acid and trans-cinnamic acid (Entry 4)

Obtained from 3-phenylpropyonic acid (146 mg, 1.00 mmol). K_2CO_3 (138 mg, 1.00 mmol) was added. The ratio of *cis*- to *trans*-cinnamic acids was estimated at 96:4 based on the intensity of the ^{1}H NMR signals at 5.95 ppm (olefin proton of *cis*-cinnamic acid) and 6.43 ppm (olefin proton of *trans*-cinnamic acid). The chemical shifts of *cis*- and *trans*-isomers were in agreement with those of the literature [50] and commercial authentic sample, respectively.

2.5.4. cis-6-Dodecene (Entry 5)

Obtained from 6-dodecyne (166 mg, 1.00 mmol). The ^{1}H NMR spectrum of the residue was identical with that of *cis*-dodecene in the literature [51].

2.5.5. cis-3-Octen-1-ol (Entry 6)

Obtained from 3-octyn-1-ol (126 mg, 1.00 mmol). The ^{1}H NMR spectrum of the residue was identical with that of commercial authentic sample.

2.5.6. cis-2,5-Dimethyl-3-hexene-2,5-diol (Entry 7)

Obtained from 2,5-dimethyl-3-hexyne-2,5-diol (142 mg, 1.00 mmol). ^{1}H NMR ($CDCl_3$) δ 5.32 (2H, s), 4.23 (2H, s), 1.37 (12H, s); ^{13}C NMR ($CDCl_3$) δ 135.4, 71.0, 31.5. MS (EI) m/z 129 (M^+-CH_3, 21%), 111 (100%), 43 (49%); HRMS (EI) Calcd. for $C_7H_{13}O_2$ (M^+-CH_3) 129.0916. Found 129.0922.

2.6. Solvent effect on the partial hydrogenation of 2-phenyl-3-butyn-2-ol (**9**) using 5% Pd(0)–PEI catalyst (Table 4)

The method described for Table 3 was followed (Section 2.5), except for the substrate and solvent. 2-Phenyl-3-butyn-2-ol (**9**, 146 mg, 1.00 mmol) and 5% Pd(0)–PEI (10 wt% of **9**, 14.6 mg) were used. The solvents used are listed in Table 4. The product ratio [**9**, 2-phenyl-3-butene-2-ol (**10**) and 2-phenyl-2-butanol (**11**)] was determined by comparison of the intensity of the three peaks at 2.65 ppm (alkyne proton of **9**), 6.17 ppm (olefin proton of **10**) and 0.80 ppm (methyl protons of **11**) in the ^{1}H NMR spectrum. The ^{1}H NMR data of **10** and **11** were in agreement with those in the literature [52] and commercial authentic sample, respectively.

2.7. Comparison between the Pd(0)–PEI catalyst and the Lindlar catalyst (Scheme 1)

2.7.1. Lindlar catalyst

In a test tube were placed 2-phenyl-3-butyn-2-ol (**9**, 146 mg, 1.00 mmol), the Lindlar catalyst (14.6 mg, 10 wt% of **9**), quinoline (129 mg, 1.00 mmol), a stirring bar, and cyclohexane (2 mL). The air inside the test tube was replaced with H_2 through three vacuum/H_2 (balloon) cycles, and the mixture was vigorously stirred at ambient temperature. After 24 h, the mixture was diluted with Et_2O (10 mL) and H_2O (10 mL), and filtered using a membrane filter (Millipore, Millex®-LH, 0.45 μm). The reaction mixture was partitioned between Et_2O (10 mL) and H_2O (10 mL) and the organic layer was washed with brine (10 mL), dried ($MgSO_4$), and filtered, then concentrated *in vacuo* to afford 2-phenyl-2-butanol (**11**) with a 100% selectivity.

2.7.2. Pd(0)–PEI catalyst

The method described above was followed, except for the Lindlar catalyst, quinoline, and cyclohexane. 5% Pd(0)–PEI (14.6 mg, 10 wt% of **9**) and 1,4-dioxane (2 mL) were used. 2-Phenyl-3-buten-2-ol (**10**) and 2-phenyl-2-butanol (**11**) were obtained in the ratio of 88:12, respectively. The product ratio was determined by comparison of the intensity of the two peaks at 6.17 ppm (olefin proton of **10**) and 0.80 ppm (methyl protons of **11**) in the ^{1}H NMR spectrum.

2.8. Typical procedure for the Pd(0)–PEI-catalyzed partial hydrogenation of mono-substituted alkynes and experimental results (Table 5)

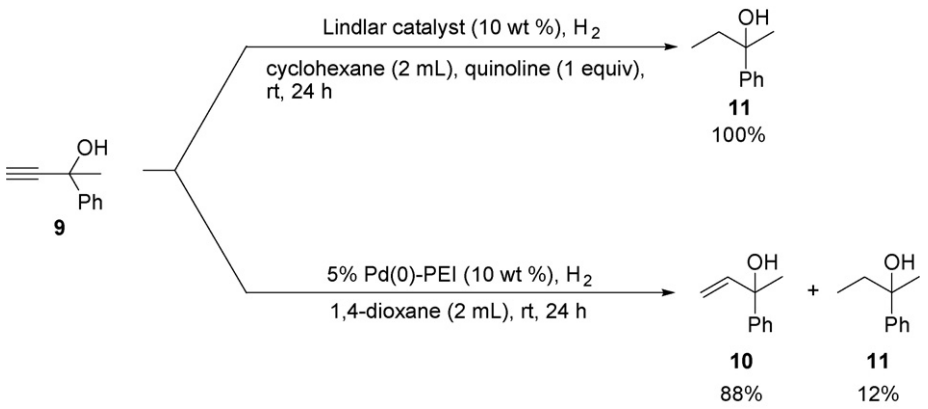
The method described for Table 3 (Section 2.5) was followed, except for substrates and solvent. The ratio of the *mono*-substituted alkyne (**12**), alkene (**13**), and alkane (**14**) was determined by a ^{1}H NMR analysis.

2.8.1. 1-Dodecene and 1-dodecane (Entry 1)

Obtained from 1-dodecyne (166 mg, 1.00 mmol). 2 mL of 1,4-dioxane was used as a solvent. The ratio of 1-dodecene and 1-dodecane was estimated at 83:17 based on intensity of the ^{1}H NMR signals at 4.94 ppm (olefin proton of 1-dodecene) and 0.88 ppm (methyl protons of 1-dodecane). These chemical shifts were in agreement with those of commercial authentic samples.

2.8.2. 4-Ethynylaniline, 4-vinylaniline and 4-ethylaniline (Entry 2)

Obtained from 4-ethynylaniline (117 mg, 1.00 mmol). 2 mL of 1,4-dioxane was used. The ratio of 4-ethynylaniline and 4-vinylaniline and 4-ethylaniline was estimated at 11:85:4 based on the intensity of the ^{1}H NMR signals at 2.95 ppm (alkyne proton of 4-ethynylaniline), 5.03 ppm (olefin proton of 4-vinylaniline) and 1.17 ppm (methyl protons of 4-ethylaniline). The chemical shifts



Scheme 1. Comparison of the Pd(0)–PEI catalyst to the Lindlar catalyst.

of these compounds were in agreement with those of commercial authentic samples.

2.8.3. Allyl(phenyl)sulfane and phenyl(n-propyl)sulfane (Entry 3)

Obtained from phenyl propargyl sulfide (148 mg, 1.00 mmol). Mixed solvent of MeOH (1 mL) and EtOAc (1 mL) was used. The ratio of allyl phenyl sulfide and phenyl propyl sulfide was estimated at 98:2 based on the intensity of the ^{1}H NMR signals at 5.09 ppm (olefin proton of allyl phenyl sulfide) and 1.02 ppm (methyl protons of phenyl propyl sulfide). These chemical shifts were in agreement with those of commercial authentic samples.

2.8.4. 9-Vinyl-9-fluorenol and 9-ethyl-9-fluorenol (Entry 4)

Obtained from 9-ethynyl-9-fluorenol (206 mg, 1.00 mmol). Mixed solvent of MeOH (0.5 mL) and 1,4-dioxane (2 mL) was used. The ratio of 9-vinyl-9-fluorenol and 9-ethyl-9-fluorenol was estimated at 88:12 based on the intensity of the ^{1}H NMR signals at 5.22 ppm (olefin proton of 9-vinyl-9-fluorenol) and 0.55 ppm (methyl protons of 9-ethyl-9-fluorenol). The chemical shifts of 9-vinyl-9-fluorenol and 9-ethyl-9-fluorenol were in agreement with those of the literature; see Refs. [53,54], respectively.

2.8.5. 17α-Vinyltestosterone [55] and 17α-ethyltestosterone [56] (Entry 5)

Obtained from ethisterone (312 mg, 1.00 mmol). Mixed solvent of MeOH (2 mL) and 1,4-dioxane (0.5 mL) was used. 5% Pd(0)–PEI (31.2 mg, 10 wt% of ethisterone). The ratio of 17α-vinyltestosterone and 17α-ethyltestosterone was estimated at 85:15 based on the intensity of the ^{1}H NMR signals at 6.01 ppm (olefin proton of 17α-vinyltestosterone) and 0.98 ppm (methyl protons of 17α-ethyltestosterone). For 17α-vinyltestosterone; ^{1}H NMR ($CDCl_3$) δ 6.01 (1H, m), 5.72 (1H, s), 5.14 (2H, m), 2.42–1.18 (22H, m), 0.96 (3H, s); MS (EI) *m/z* 314 (M^+, 100%), 299 (21%), 281 (19%), 245 (42%); HRMS (EI) Calcd. for $C_{21}H_{30}O_2$ (M^+) 314.22458. Found 314.22417. Anal. Calcd. for $C_{21}H_{30}O_2$: C, 80.21; H, 9.62. Found C, 80.04; H, 9.77. For 17α-ethyltestosterone; ^{1}H-NMR ($CDCl_3$) δ 5.72 (1H, s), 2.42–1.18 (24H, m), 0.98 (3H, t, J = 7.4 Hz), 0.93 (3H, s); MS (EI) *m/z* 316 (M^+, 100%), 298 (13%), 287 (14%), 245 (31%), 229 (33%); HRMS (EI) Calcd. for $C_{21}H_{32}O_2$ (M^+) 316.24023. Found 316.24101.

2.8.6. 17α-Vinylestradiol (Entry 6)

Obtained from ethynylestradiol (296 mg, 1.00 mmol). K_2CO_3 (138 mg, 1.00 mmol) and the mixed solvent of MeOH (2 mL) and 1,4-dioxane (0.5 mL) were used. The ^{1}H NMR spectrum of the residue was identical with that in the literature [57].

2.8.7. 6-Heptenoic acid and heptanoic acid (Entry 7)

Obtained from 6-heptynoic acid (126 mg, 1.00 mmol). K_2CO_3 (138 mg, 1.00 mmol) and 2 mL of 1,4-dioxane were used. The ratio of 6-heptynoic acid and 6-heptenoic acid and heptanoic acid was estimated at 9:73:18 based on the intensity of the ^{1}H NMR signals at 1.98 ppm (alkyne proton of 6-heptynoic acid) and 5.78 ppm (olefin proton of 6-heptenoic acid) and 0.89 ppm (methyl protons of heptanoic acid). These chemical shifts were in agreement with those of commercial authentic samples.

2.8.8. Allyl benzoate and n-propyl benzoate (Entry 8)

Obtained from propargyl benzoate (160 mg, 1.00 mmol). Mixed solvent of MeOH (1.5 equiv.) and 1,4-dioxane (2 mL) was used. The ratio of allyl benzoate and *n*-propyl benzoate was estimated at 83:17 based on the intensity of the ^{1}H NMR signals at 5.38 ppm (olefin proton of allyl benzoate) and 1.02 ppm (methyl protons of *n*-propyl benzoate). The chemical shifts of allyl benzoate and *n*-propyl benzoate were in agreement with those of the literature [58] and commercial authentic sample, respectively.

2.8.9. Dimethyl(phenyl)(vinyl)silane and ethyldimethyl(phenyl)silane (Entry 9)

Obtained from (dimethylphenylsilyl)acetylene (160 mg, 1.00 mmol). Mixed solvent of MeOH (1 equiv.) and 1,4-dioxane (2 mL) was used. The ratio of dimethyl(phenyl)(vinyl)silane and ethyldimethyl(phenyl)silane was estimated at 77:23 based on the intensity of the ^{1}H NMR signals at 5.74 ppm [olefin proton of dimehyl(phenyl)(vinyl)silane] and 0.95 ppm [methyl protons of ethyldimethyl(phenyl)silane]. The chemical shifts of dimethyl(phenyl)(vinyl)silane and ethyldimethyl(phenyl)silane were in agreement with those of the literature; see Refs. [59,60], respectively.

2.9. Synthesis of the substrates (Table 6)

2.9.1. N-Benzyloxycarbonyl-4-ethynylaniline (Entries 1 and 2)

To a solution of 4-ethynylaniline (586 mg, 5.00 mmol) in THF (10.0 mL) was added *N*-(benzyloxycarbonyloxy)succinimide (1.50 g, 6.00 mmol). After 16 h, the mixture was partitioned between EtOAc (150 mL) and H_2O (100 mL). The organic layer was washed with brine (100 mL), dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was purified by flash column chromatography on silica gel (*n*-hexane/Et_2O, 10/1) to give *N*-benzyloxycarbonyl-4-ethynylaniline (1.17 g, 93%) as a pale brownish yellow solid. The ^{1}H NMR data was identical with that of the literature [41].

2.9.2. Benzyl 6-heptynoate (Entries 3 and 4)

To a solution of 6-heptynoic acid (1.26 g, 10.0 mmol), 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDC·HCl) (1.92 g, 10.0 mmol), and 4-(dimethylamino)pyridine (DMAP) (122 mg, 1.00 mmol) in CH_2Cl_2 (20.0 mL) was added benzyl alcohol (1.08 g, 10.0 mmol). After 44 h, the mixture was partitioned between EtOAc (150 mL) and H_2O (100 mL). The organic layer was washed with brine (100 mL), dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was purified by flash column chromatography on silica gel (*n*-hexane/Et_2O, 20/1) to give benzyl 6-heptynoate (1.82 g, 84%) as a pale yellow oil. The ^{1}H NMR data was identical with that of the literature [61].

2.9.3. 4-(Benzyloxy)butyne (Entries 5 and 6)

To a suspension of NaH (60%, w/w in mineral oil, 300 mg, 7.50 mmol) in THF (5.00 mL) and DMF (4.00 mL) was added a THF solution (5.00 mL) of 3-butyn-1-ol (351 mg, 5.00 mmol) at 0 °C. After 30 min, the resulting solution was stirred at rt for 1 h, benzyl bromide (1.31 g, 7.50 mmol) was added dropwise, and the mixture was stirred at 0 °C for 30 min then at room temperature for 16 h. The mixture was partitioned between Et_2O (150 mL) and H_2O (100 mL). The organic layer was washed with brine (100 mL), dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The residue was purified by flash column chromatography on silica gel (*n*-hexane/Et_2O, 20/1) to give 4-(benzyloxy)butyne (766 mg, 96%) as a pale yellow oil. The ^{1}H NMR data was identical with that of the literature [62].

2.9.4. 2-tert-Butyldimethylsilyloxy-2-phenyl-3-butyne (Entries 7–10)

To a solution of 2-phenyl-3-butyn-2-ol (731 mg, 5.00 mmol) and 2,6-lutidine (1.07 g, 10.0 mmol) in CH_2Cl_2 (5.00 mL) was added dropwise *tert*-butyldimethylsilyl trifluoromethanesulfonate (1.98 g, 7.5 mmol) at 0 °C under argon atmosphere and the mixture was stirred at rt. After 30 min the mixture was partitioned between Et_2O (150 mL) and H_2O (100 mL). The organic layer was washed with brine (100 mL), dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The residue was purified by flash column chromatography on silica gel (*n*-hexane) to give 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne (1.24 g, 95%) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ 7.63 (2H, d, J = 8.2 Hz), 7.35–7.26 (3H, m), 2.66 (1H, s), 1.73 (3H, s), 0.93 (9H, s), 0.21 (3H, s), 0.03 (3H, s); ^{13}C NMR ($CDCl_3$) δ 146.9, 128.3, 127.5, 125.3, 88.0, 74.4, 71.2, 36.0, 26.2, 18.6, −2.5, −2.9; MS (EI) *m*/*z* 245 (M^+-CH_3, 6%), 203 (100%), 129 (13%), 75 (59%); HRMS (EI) Calcd. for $C_{15}H_{21}OSi$ (M^+-CH_3) 245.1362. Found 245.1370.

2.10. Chemoselective hydrogenation between mono-substituted alkynes and other reducible functionalities and experimental results (Table 6)

The method described for Table 3 (Section 2.5) was followed, except for substrates and solvent. The ratio of the starting alkyne (**15**), the alkene and alkane with a reducible functionality (**16** and **17**), and the alkene and alkane with a reduced functionality (**18** and **19**) was determined by a ^{1}H NMR analysis.

2.10.1. N-Benzyloxycarbonyl-4-vinylaniline and N-benzyloxycarbonyl-4-ethylaniline (Entry 2)

Obtained from *N*-benzyloxycarbonyl-4-ethynylaniline (126 mg, 0.50 mmol). Mixed solvent of MeOH (0.25 mL) and 1,4-dioxane (1 mL) was used. The ratio of *N*-benzyloxycarbonyl-4-vinylaniline and *N*-benzyloxycarbonyl-4-ethylaniline was estimated at 93:7 based on the intensity of the ^{1}H NMR signals at 5.68 ppm (olefin proton of *N*-benzyloxycarbonyl-4-vinylaniline) and 1.21 ppm (methyl protons of *N*-benzyloxycarbonyl-4-ethylaniline). These chemical shifts were in agreement with those of the literature [41].

2.10.2. Benzylheptynoate and benzylheptenoate (Entry 3)

Obtained from benzyl 6-heptynoate (108 mg, 0.50 mmol). 1 mL of 1,4-dioxane was used. The ratio of benzylheptynoate and benzylheptenoate was estimated at 87:13 based on the intensity of the ^{1}H NMR signals at 1.94 ppm (acetylene proton of benzylheptynoate) and 4.98 ppm (olefin proton of benzylheptenoate). These chemical shifts were in agreement with those of the literature [61] and those indicated in Section 2.10.3.

2.10.3. Benzyl heptenoate (Entry 4)

Obtained from benzyl 6-heptynoate (108 mg, 0.50 mmol). Mixed solvent of MeOH (0.25 mL) and 1,4-dioxane (1 mL) was used. ^{1}H NMR ($CDCl_3$) δ 7.39–7.30 (5H, m), 5.83–5.73 (1H, m), 5.12 (2H, s), 4.98 (2H, m), 2.37 (2H, t, J = 7.7 Hz), 2.06 (2H, m), 1.67 (2H, m), 1.46–1.38 (2H, m); MS (EI) *m*/*z* 218 (M^+, 2%), 91 (100%); HRMS (EI) Calcd. for $C_{14}H_{18}O_2$ (M^+) 218.1307. Found 218.1295.

2.10.4. 4-(Benzyloxy)butyne and 4-(benzyloxy)butene (Entry 5)

Obtained from 4-(benzyloxy)butyne (80.0 mg, 0.50 mmol). 1 mL of 1,4-dioxane was used. The ratio of 4-(benzyloxy)butyne and 4-(benzyloxy)butene was estimated at 67:33 based on the intensity of the ^{1}H NMR signals at 1.99 ppm [acetylene proton of 4-(benzyloxy)butyne)] and 5.08 ppm [olefin proton of 4-(benzyloxy)butane]. These chemical shifts of 4-(benzyloxy)butyne and 4-(benzyloxy)butene were in agreement with those of the literature [62,63], respectively.

2.10.5. 4-(Benzyloxy)butene and benzyl butyl ether (Entry 6)

Obtained from 4-(benzyloxy)butyne (80.0 mg, 0.50 mmol). Mixed solvent of MeOH (0.25 mL) and 1,4-dioxane (1 mL) was used. The ratio of 4-(benzyloxy)butene and benzyl butyl ether was estimated at 96:4 based on the intensity of the ^{1}H NMR signals at 5.08 ppm (olefin proton of 4-(benzyloxy)butene) and 3.48 ppm (methylene protons of benzyl butyl ether). These chemical shifts of 4-(benzyloxy)butene and benzyl butyl ether were in agreement with those of the literature [63] and commercial authentic sample, respectively.

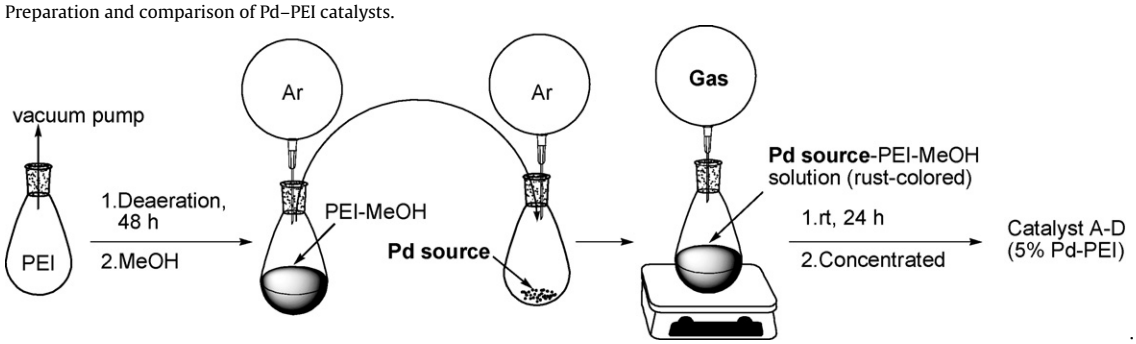
2.10.6. 2-tert-Butyldimethylsilyloxy-2-phenyl-3-butyne and 2-tert-butyldimethylsilyloxy-2-phenyl-3-butene (Entry 8)

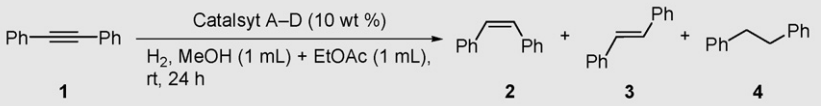
Obtained from 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne (130 mg, 0.5 mmol). Mixed solvent of MeOH (0.25 mL) and 1,4-dioxane (1 mL) was used. The ratio of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne and 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butene was estimated at 71:29 based on the intensity of the ^{1}H NMR signals at 2.66 ppm (acetylene proton of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne) and 5.99 ppm (olefin protons of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butene). These chemical shifts of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne and 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butene were in agreement with those indicated in Sections 2.9.4 and 2.10.8, respectively.

2.10.7. 2-tert-Butyldimethylsilyloxy-2-phenyl-3-butyne and 2-tert-butyldimethylsilyloxy-2-phenyl-3-butene (Entry 9)

Obtained from 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne (130 mg, 0.5 mmol). Mixed solvent of MeOH (1 mL) and 1,4-dioxane (0.25 mL) was used. The ratio of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne and 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butene was determined to be 9:91 based on the intensity of the ^{1}H NMR signals at 2.66 ppm (acetylene proton of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne) and 5.99 ppm (olefin protons of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butene). These chemical shifts of 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne and 2-

Table 1
Preparation and comparison of Pd–PEI catalysts.





Entry	Pd source	Gas	1:2:3:4[a]
1	$Pd(OAc)_2$	Ar (catalyst A)	95:5:0:0
2	$Pd(OAc)_2$	H_2 (catalyst B)	0:95:1:4
3	$PdCl_2$	H_2 (catalyst C)	5:91:2:2
4	$Pd(PPh_3)_4$	Ar (catalyst D)	79:19:1:1

[a] The ratio was determined by ^{1}H NMR analysis.

tert-butyldimethylsilyloxy-2-phenyl-3-butene were in agreement with those indicated in Sections 2.9.4 and 2.10.8, respectively.

2.10.8. 2-tert-Butyldimethylsilyloxy-2-phenyl-3-butene (Entry 10)

Obtained from 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne (130 mg, 0.5 mmol). 1 mL of MeOH was used. ^{1}H NMR ($CDCl_3$) δ 7.44–7.20 (5H, m), 5.99 (1H, dd, J = 17.2, 10.5 Hz), 5.27 (1H, dd, J = 17.2, 1.0 Hz), 5.09 (1H, dd, J = 10.5, 1.0 Hz), 1.65 (3H, s), 0.95 (9H, s), 0.05 (3H, s), 0.00 (3H, s); MS (EI) m/z 247 (M^+-CH_3, 6%), 205 (98%), 131 (20%), 91 (11%), 75 (100%), 44 (14%); HRMS (EI) Calcd. for $C_{15}H_{23}OSi$ (M^+-CH_3) 247.1518. Found 247.1509.

*2.11. Effect of acetic acid toward Pd(0)–PEI-catalyzed partial hydrogenation of **1** (Table 7)*

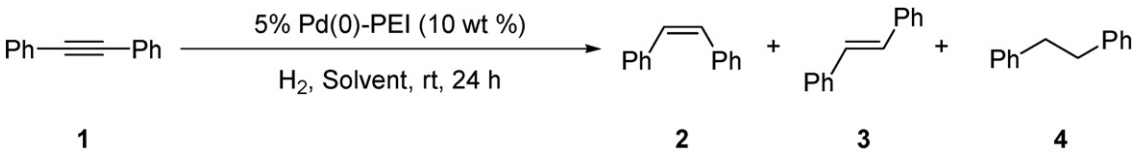
Entry 1: The method described for Table 3 (Section 2.5) was followed, except for substrates and solvent. The ratio of the diphenylacetylene (**1**), *cis*-stilbene (**2**), *trans*-stilbene (**3**), and 1,2-diphenylethane (**4**) was determined by a ^{1}H NMR analysis.

Entry 2: In a test tube were placed diphenylacetylene (**1**, 178 mg, 1.00 mmol), 5% Pd(0)–PEI (17.8 mg, 10 wt% of **1**), a stirring bar, AcOH (57.0 μL, 1.00 mmol), MeOH (1 mL), and EtOAc (1 mL). The air inside the test tube was replaced with H_2 by three vacuum/H_2 (balloon) cycles, and then the mixture was vigorously stirred at ambient temperature. After 24 h, the reaction mixture was partitioned between Et_2O (10 mL) and H_2O (10 mL), and the organic layer was washed with brine (10 mL), dried ($MgSO_4$), filtered, and concentrated *in vacuo* to afford the residue composed of the diphenylacetylene (**1**), *cis*-stilbene (**2**), *trans*-stilbene (**3**), and 1,2-diphenylethane (**4**). The ratio of the diphenylacetylene (**1**), *cis*-stilbene (**2**), *trans*-stilbene (**3**), and 1,2-diphenylethane (**4**) was determined by a ^{1}H NMR analysis.

3. Results and discussion

At the outset of this research, we established the method for preparing the 5% Pd–PEI catalyst by adopting a modified procedure for the preparation of the Pd-fibroin (Pd-Fib) catalyst reported by us [39–42]. First, PEI (2.11 g) was deaerated under reduced pressure for 48 h and slowly dissolved in MeOH under an argon atmosphere. The resulting colorless solution was poured into a round-bottom

Table 2
Solvent effect on the 5% Pd(0)–PEI catalyzed partial hydrogenation.



Entry	Solvent	1:2:3:4[a]
1	Cyclohexane (2 mL)	100:0:0:0
2	EtOAc (2 mL)	100:0:0:0
3	1,4-Dioxane (2 mL)	100:0:0:0
4	MeOH (2 mL)	0:68:2:30
5	MeOH (2 mL) + 1,4-dioxane (0.5 mL)	0:72:4:24
6	MeOH (2 mL) + EtOAc (0.5 mL)	0:82:2:16
7	MeOH (1 mL) + EtOAc (1 mL)	0:95:1:4
8	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:97:1:2

[a] The ratio was determined by ^{1}H NMR analysis.

flask containing $Pd(OAc)_2$ (225 mg) under argon. After dissolution of $Pd(OAc)_2$ in the PEI–MeOH solution, the generated rust-colored solution was stirred at room temperature for 24 h and then concentrated *in vacuo* to give a yellow gum (Table 1, Entry 1: catalyst A, Pd content of ca. 5%). The activity of catalyst A was then tested. A mixture of diphenylacetylene (**1**) in the mixed solvent of MeOH (1 mL) and EtOAc (1 mL) was stirred with catalyst A (10% of the weight of **1**) under a hydrogen (balloon) atmosphere, but the reaction scarcely proceeded. These results suggest that $Pd(OAc)_2$ was not sufficiently reduced to the active Pd(0) species by MeOH [39–42] during the preparation processes of the catalyst. Furthermore, the Pd(II) species of the Pd(II)–PEI complex were hardly reduced to the active Pd(0) species even under the hydrogenation conditions. On the other hand, when $Pd(OAc)_2$ was treated with PEI under a hydrogen atmosphere, a black gummy material (catalyst B) was obtained and smoothly catalyzed the hydrogenation of **1** to afford *cis*-stilbene (**2**) with an excellent selectivity (95%, Entry 2). $PdCl_2$ was also used

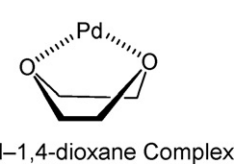


Fig. 1. Plausible structure of the Pd–1,4-dioxane complex.

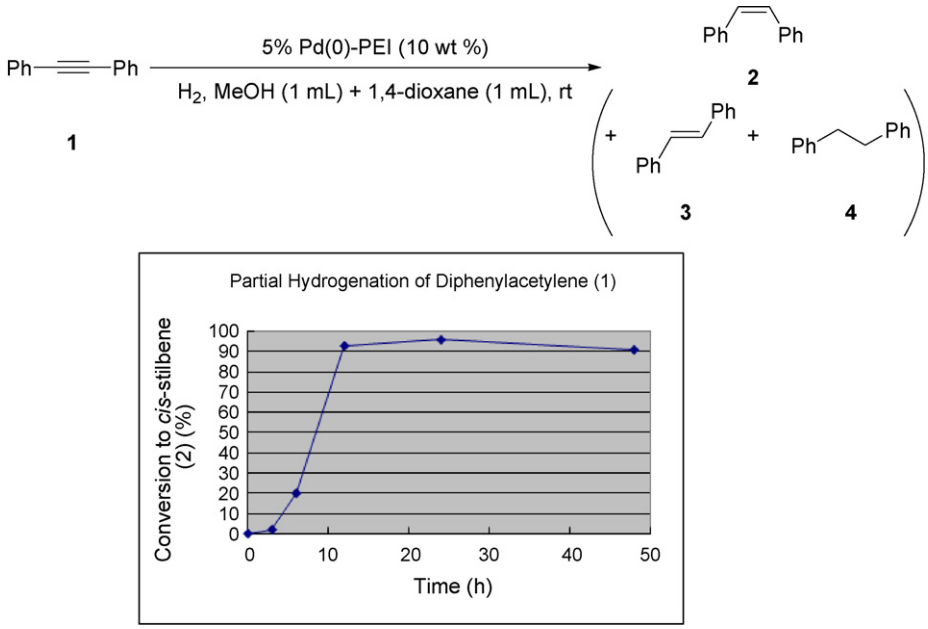
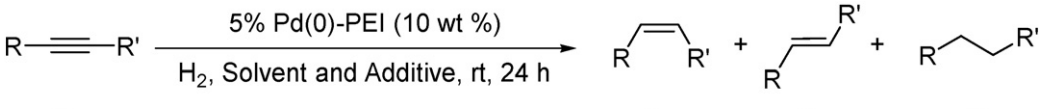


Fig. 2. Time course study on the 5% Pd(0)–PEI catalyzed hydrogenation.

Table 3
Partial hydrogenation of various *di*-substituted alkynes using 5% Pd(0)–PEI catalyst.

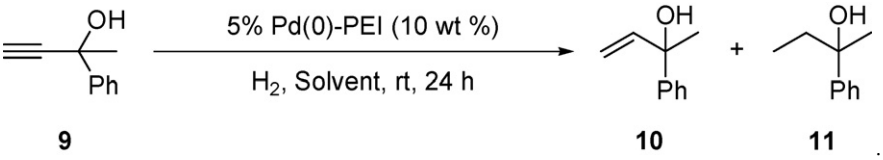


5 6 7 8

Entry	Substrate	Solvent and additive	**5**:**6**:**7**:**8**[a]
1	Ph—≡—CO_2Et	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:94:0:6
2	Ph—≡—COMe	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:36:58:6
3	Ph—≡—CO_2H	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:0:0:100
4		MeOH (1 mL) + 1,4-dioxane (1 mL) + K_2CO_3 (1 equiv.)	0:96:4:0
5	C_5H_{11}—≡—C_5H_{11}	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:100:0:0
6	C_4H_9—≡—$(CH_2)_2OH$	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:100:0:0
7	HO, OH	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:100:0:0
8		MeOH (1 mL) + 1,4-dioxane (1 mL)	70:24:0:6
9	Ph—≡—TMS	MeOH (2 mL) + 1,4-dioxane (0.5 mL)	57:27:0:16
10		MeOH (2 mL)	0:0:0:100

[a] The ratio was determined by ^1H NMR analysis.

Table 4
Solvent effect on the partial hydrogenation of 2-phenyl-3-butyn-2-ol (**9**) using 5% Pd(0)–PEI catalyst.



9 **10** **11**

Entry	Solvent	**9**:**10**:**11**[a]
1	MeOH (1 mL) + 1,4-dioxane (1 mL)	0:34:66
2	MeCN (1 mL) + 1,4-dioxane (1 mL)	2:76:22
3	EtOAc (2 mL) + benzene (0.5 mL)	4:82:14
4	EtOAc (2 mL)	5:82:13
5	EtOAc (2 mL) + toluene (0.5 mL)	0:86:14
6	1,4-Dioxane (2 mL)	0:88:12

[a] The ratio was determined by ^{1}H NMR analysis.

for the catalyst preparation as a Pd source (Entry 3). The generated catalyst C exhibited a catalytic activity and selectivity comparable to those of catalyst B, although the heating conditions of 90 °C were required for its preparation due to the poor solubility of $PdCl_2$ in MeOH. In contrast, catalyst D, which was prepared from $Pd(PPh_3)_4$, a Pd(0) source, under an argon atmosphere, was not active enough to promote the hydrogenation of **1** (Entry 4). Therefore, we chose catalyst B as the 5% Pd(0)–PEI complex catalyst for the chemoselective hydrogenation.

We next investigated the solvent effect on the hydrogenation (Table 2). The reduction of diphenylacetylene (**1**) never proceeded in aprotic solvents such as cyclohexane, EtOAc and 1,4-dioxane at room temperature, while a mixture of *cis*-stilbene (**2**) and the fully reduced 1,2-diphenylethane (**4**) was obtained in MeOH in the ratio of 68:30 (Entries 1–4). We then tested the hydrogenation in mixed solvents such as MeOH and either EtOAc or 1,4-dioxane (Entries 5–8). To our delight, **2** was efficiently obtained in MeOH–1,4-dioxane (1:1) accompanied by a 97% chemoselectivity (Entry 8). The catalytic activity of 5% Pd(0)–PEI might be moderately deactivated by coordination of the bulk 1,4-dioxane with the palladium species (Fig. 1).

We also conducted time course study on the reduction of **1** using the 5% Pd(0)–PEI catalyst (Fig. 2). Hydrogenation of **1** gradually proceeded, and **2** was obtained with a 97% selectivity after 24 h. Further extension of the reaction time led to virtually no variation in the product ratio.

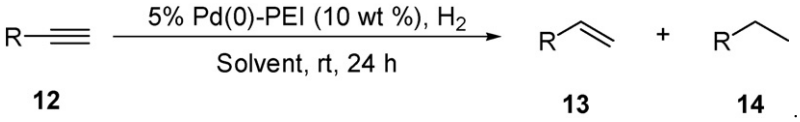
To evaluate the applicable scope of the Pd(0)–PEI catalyst, we carried out the partial hydrogenation of various *di*-substituted alkynes in MeOH–1,4-dioxane (1:1) (Table 3). Ethyl 3-phenylpropionate was partially hydrogenated to the corresponding *cis*-alkene (Entry 1). Although the hydrogenation of 4-phenyl-3-butyn-2-one afforded a mixture of geometrical isomers of the resulting alkenes (*cis*:*trans* = 4:6), over-hydrogenation was hardly observed (Entry 2). The isomerization of the resulting α,β-unsaturated ketone (**6**) via a π–palladium complex would produce the thermodynamically stable *trans*-isomer (**7**). A complete overreduction to the corresponding alkane took place under the optimized reaction conditions, when phenyl propionic acid was used as the substrate. This is presumably due to the destruction of the coordination of the nitrogen lone pair of PEI to the Pd(0) metal center by the carboxylic proton (Entry 3). In contrast, the addition of 1 equivalent of K_2CO_3 to the present reaction conditions resulted in the 96% selectivity of the desired *cis*-alkene without overreduction (Entry 4). A variety of internal alkynes including hydroxyl-containing (Entries 6 and 7) and sterically bulky substituents (Entry 7) were selectively hydrogenated to the corresponding alkenes under the optimized conditions (Entries 5–7). These results indicated that the 5% Pd(0)–PEI catalyst is applicable for the partial hydrogenation of various *di*-substituted alkynes. Exceptionally, 1-phenyl-2-trimethylsilylacetylene, a silylated alkyne, was resistant to the hydrogenation (Entry 8). The hydrogenation efficiency of the alkyne was increased with increasing MeOH content, but the chemoselective hydrogenation could not be achieved (Entries 9 and 10).

The results shown in Table 3 encouraged us to investigate the partial hydrogenation of *mono*-substituted alkynes; i.e., 2-phenyl-3-butyn-2-ol (**9**) was subjected to the 5% Pd(0)–PEI catalyzed-hydrogenation conditions in MeOH (1 mL) and 1,4-dioxane (1 mL) (Table 4, Entry 1). Unfortunately, an overreduction readily took place forming the corresponding alkane in 66% selectivity. We then examined the use of solvents possessing a coordinating ability based upon π-electrons or lone pairs in place of MeOH to further reduce the catalyst activity. When MeOH of the MeOH–1,4-dioxane (1:1) mixed solvent was replaced with MeCN, the selectivity of the partial hydrogenation was dramatically increased to 76% (Entry 2). Further improvement was observed with the use of EtOAc, benzene, and/or toluene as the solvents (Entries 3–5). The best result was obtained in 1,4-dioxane as a single solvent (Entry 6) since 1,4-dioxane would coordinate with Pd metal to possibly form the Pd–1,4-dioxane complex shown in Fig. 1 and act as an efficient catalyst poison to avoid any overreduction.

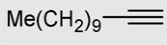
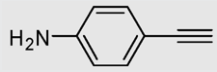
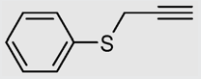
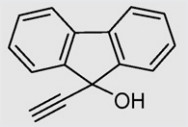
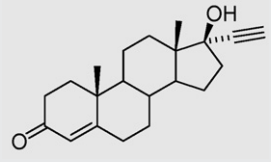
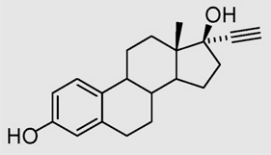
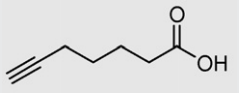
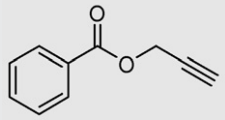
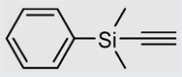
On the other hand, the hydrogenation of **9** with the Lindlar catalyst in the presence of quinoline as an additive in cyclohexane led to the quantitative formation of the corresponding alkane **11** (Scheme 1). These results indicate that the Pd(0)–PEI catalyst is superior to the Lindlar catalyst in selectivity for the partial hydrogenation of *mono*-substituted alkynes.

To demonstrate the scope and limitation, we investigated the 5% Pd(0)–PEI-catalyzed partial hydrogenation of a variety of *mono*-substituted alkynes (Table 5). Aliphatic and aromatic alkynes were readily hydrogenated to the corresponding alkenes with good selectivities (Entries 1 and 2). The hydrogenation of a sulfur-containing substrate also afforded the desired alkene in a 98% selectivity, even though a sulfur element was commonly considered to inhibit the Pd-catalyzed hydrogenations as a strong catalyst poison (Entry 3). Bulky *mono*-substituted alkynes possessing a fluorene (Entry 4) or steroid (Entry 5) framework were also partially hydrogenated with good selectivities in the MeOH–1,4-dioxane mixed solvents and the intramolecular α,β-unsaturated ketone of ethisterone was totally untouched (Entry 5). In the case of the partial hydrogenation of ethynylestradiol (Entry 6) and 6-heptynoic acid (Entry 7), the addition of K_2CO_3 was essential in obtaining a good to excellent selectivity. It would scavenge the acidic proton of the phenolic hydroxyl or carboxylic acid functionality in a manner similar to the carboxylic acid in Entry 4, Table 3. The partial hydrogenations of propargyl benzoate and dimethylphenylsilylacetylene were controlled by the addition of a small amount of MeOH (Entries 8 and

Table 5
Pd(0)–PEI catalyzed partial hydrogenation of various *mono*-substituted alkynes.



12 **13** **14**

Entry	Substrate	Solvent and additive	**12**:**13**:**14**[a]
1		1,4-Dioxane (2 mL)	0:83:17
2		1,4-Dioxane (2 mL)	11:85:4
3		MeOH (1 mL) + EtOAc (1 mL)	0:98:2
4		MeOH (0.5 mL) + 1,4-dioxane (2 mL)	0:88:12
5		MeOH (2 mL) + 1,4-dioxane (0.5 mL)	0:85:15
6		MeOH (2 mL) + 1,4-dioxane (0.5 mL) + K_2CO_3 (1 equiv.)	0:100:0
7		1,4-Dioxane (2 mL) + K_2CO_3 (1 equiv.)	9:73:18
8		MeOH (1.5 equiv.) + 1,4-dioxane (2 mL)	0:83:17
9		MeOH (1 equiv.) + 1,4-dioxane (2 mL)	0:77:23

[a] The ratio was determined by ^{1}H NMR analysis.

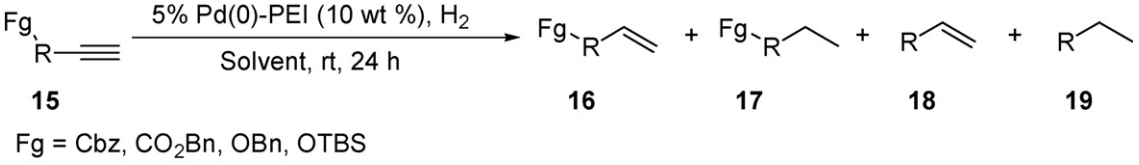
9). It is now apparent that the Pd(0)–PEI catalyst is quite suitable for the partial hydrogenation of not only *di*-substituted alkynes but also *mono*-substituted alkynes.

Chemoselective hydrogenation is one of the powerful tools in synthetic organic chemistry. We next examined the catalytic property of 5% Pd(0)–PEI toward the partial hydrogenation of alkynes in the presence of other reducible functionalities within the molecule (Table 6). Although the partial hydrogenation of the alkyne functional groups of *N*-benzyloxycarbonyl-4-ethynylaniline (Entry 1), benzyl 6-heptynoate (Entry 3) and 4-(benzyloxy)butyne (Entry 5) were incomplete in 1,4-dioxane as a single solvent, the highly chemoselective hydrogenation of only alkynes was achieved with the Cbz, benzyl ester, and benzyl ether functionalities untouched by the use of MeOH–1,4-dioxane (1:4) mixed solvent (Entries 2, 4, and 6). When 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne was used as a substrate even in MeOH–1,4-dioxane (1:4–4:1), the reaction was not completed presumably due to the steric hindrance of the *O*-TBS group (Entries 8 and 9). Such a drawback was alleviated by the use of MeOH as a single solvent in place of a diluted MeOH with 1,4-dioxane, and the desired product (**16**) was selectively obtained without removal of the *O*-TBS protective group (Entry 10). In the cases of sterically hindered substrates such as 2-*tert*-butyldimethylsilyloxy-2-phenyl-3-butyne, alkynes are difficult to approach to the active site on Pd (compare the results of Table 4, Entries 1 and 6 to Table 6, Entries 7–9).

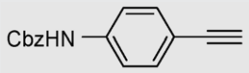
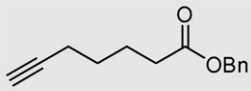
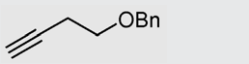
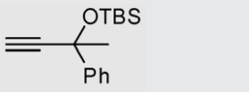
The partial hydrogenation was strongly influenced by the addition of acetic acid. While *cis*-stilbene (**2**) was obtained by the Pd(0)–PEI catalyzed partial hydrogenation of diphenylacetylene (**1**) in MeOH–EtOAc (1:1) as a solvent (Table 7, Entry 1), the drastic overreduction to 1,2-diphenylethane (**4**) proceeded by the addition of acetic acid (1 equiv vs. substrate) into the reaction mixture (Entry 2).

A postulated mechanistic image for the present Pd(0)–PEI-catalyzed partial hydrogenation of alkynes is shown in Fig. 3.

Table 6
Pd(0)–PEI catalyzed chemoselective hydrogenation between *mono*-substituted alkynes and other reducible functionalities.

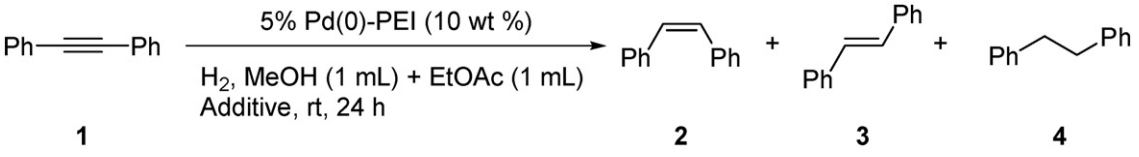


.

Entry	Substrate	Solvent	**15**:**16**:**17**:**18**:**19**[a]
1		1,4-Dioxane (1 mL)	100:0:0:0:0
2		MeOH (0.25 mL) + 1,4-dioxane (1 mL)	0:93:7:0:0
3		1,4-Dioxane (1 mL)	87:13:0:0:0
4		MeOH (0.25 mL) + 1,4-dioxane (1 mL)	0:100:0:0:0
5		1,4-Dioxane (1 mL)	67:33:0:0:0
6		MeOH (0.25 mL) + 1,4-dioxane (1 mL)	0:96:4:0:0
7		1,4-Dioxane (1 mL)	100:0:0:0:0
8		MeOH (0.25 mL) + 1,4-dioxane (1 mL)	71:29:0:0:0
9		MeOH (1 mL) + 1,4-dioxane (0.25 mL)	9:91:0:0:0
10		MeOH (1 mL)	0:100:0:0:0

[a] The ratio was determined by ^{1}H NMR analysis.

Table 7
Effect of acetic acid on Pd(0)–PEI-catalyzed partial hydrogenation of **1**.



.

Entry	Additive	**1**:**2**:**3**:**4**[a]
1	None	0:95:1:4
2	AcOH (1 equiv.)	0:16:5:79

[a] The ratio was determined by ^{1}H NMR analysis.

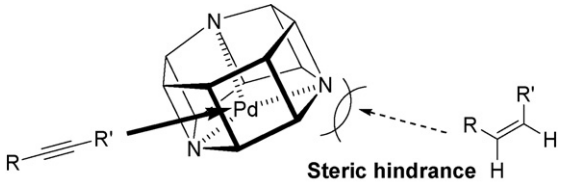


Fig. 3. Postulated mechanistic image for the chemoselectivity.

The formation of a complex of Pd(0) metal and nitrogen atoms of PEI produces the Pd(0)–PEI complex possessing a gentle wire-gauze-like equilibrium structure. Furthermore, enormous amounts of 1,4-dioxane as a solvent could patch up the open-seam of the Pd(0)–PEI complex as a bidentate oxygen ligand. On the other hand, the addition of acetic acid into the reaction mixture causes the destruction of the coordinate bonds (see Table 7). It is speculated that the PEI-gauze keeps alkenes possessing sp^2-carbons well away from strongly occluded Pd(0) metal although the spatially compact alkynes can easily access catalytically active sites.

4. Conclusion

We have developed 5% Pd(0)–PEI for the partial hydrogenation of alkynes. 5% Pd(0)–PEI is easy to prepare and stable in a regular screw cap vial at room temperature. It catalyzes only the hydrogenation of alkynes to alkenes leaving the other reducible functionalities intact. It is noteworthy that the *mono*-, and *di*-substituted alkynes can coexist with other reducible functionalities. These results reinforce the utility of alkynes as important synthons and the chemoselective hydrogenation catalyst, 5% Pd(0)–PEI, which should find a broad range of organic chemistry applications.

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