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Assembled catalyst of palladium and non-cross-linked amphiphilic polymer ligand for the efficient heterogeneous Heck reaction

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Abstract—The efficient heterogeneous Heck reaction was achieved by a new networked and supramolecular catalyst PdAS-V (**1b**). Employing of PdAS-V in 5.0×10^{-5} mol equiv. efficiently progressed the heterogeneous Heck reaction of a series of aryl iodides with acrylates, styrenes and acrylic acid. PdAS-V was successfully recycled five times without any decrease in its activity, and showed good stability in toluene and water, and hence the Heck reaction was efficiently performed in both reaction media. The use of 8.0×10^{-7} mol equiv. of PdAS-V resulted in the coupling product in 92% yield with the turnover number (TON) and the turnover frequency (TOF) of PdAS-V reached up to 1,150,000 and 12,000, respectively. The efficient synthesis of resveratrol was achieved via the PdAS-V-promoted Heck reaction.

1. Introduction

Development of reusable and solid-phase palladium catalysts is a very important theme in recent organic chemistry and industrial process.[1,2] Although homogeneous palladium catalysts are widely used and essential in organic synthesis, they have several drawbacks to be resolved. For example, palladium is an expensive and precious metal so that disposable palladium catalysts are wasteful, and perfect removal of palladium from a reaction mixture is bothersome and difficult, resulting in contamination of the products and the waste fluid by palladium. By contrast, reusable and solid-phase palladium catalysts, in an ideal system, will resolve these problems: such palladium catalysts are reused infinitely; a work-up of the reaction is simple and easy; they are recovered from the reaction mixture by simple filtration. Therefore, many immobilized and insoluble palladium catalysts have been reported, which were supported mainly onto insoluble resins, silica gels and metal oxides. Their catalytic system, however, has not been established in reality. Their catalytic activity is generally lower than that of homogeneous counterparts. Besides, they have a tendency to decrease the catalytic activity of themselves in repeated use owing to leaching of metal species from their supports.[2]

We conceived that new structural design and methodology to develop highly active, reusable and solid-phase palladium catalysts should be needed. The traditional resin or silica gel-supported palladium catalysts are prepared by the linking of palladium species onto insoluble supports (Scheme 1, above). On the other hand, we focused on a different strategy: self-assembled process between non-cross-linked amphiphilic polymer ligands and palladium to prepare the solid-phase catalysts (Scheme 1, below).[3] This process was expected to produce networked and supramolecular complexes where the polymers were cross-linked by palladium. Based on our strategy, PdAS (**1a**), a supramolecular complex of $(NH_4)_2PdCl_4$ (**2**) and poly[(*N*-isopropylacrylamide)$_{10}$-*co*-(4-diphenylstyrylphosphine)] (**3a**)), was developed as a solid-phase catalyst for the heterogeneous Suzuki–Miyaura reaction.[3c] PdAS, used in 8×10^{-7}–5×10^{-4} mol equiv., catalyzed efficiently the coupling, and was recycled 10 times without declining the catalytic activity.

Since PdAS was a highly active and reusable catalyst, we focused on its application to the efficiently recycled system of the Heck reaction. The Heck reaction, the coupling of sp^2-halides with alkenes promoted by palladium catalysts, is an important reaction for the synthesis of natural products and bioactive compounds as well as for the industrial process chemistry.[4] Although many efforts to prepare solid-phase catalysts for the Heck reaction have been made, homogeneous catalytic systems have advantages on catalytic activity.[5] In fact, it was known that designing recyclable system for the Heck reaction was more

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Keywords: *N*-Isopropylacrylamide; Heck reaction; Palladium and compounds; Polymer support; Self-assembly.

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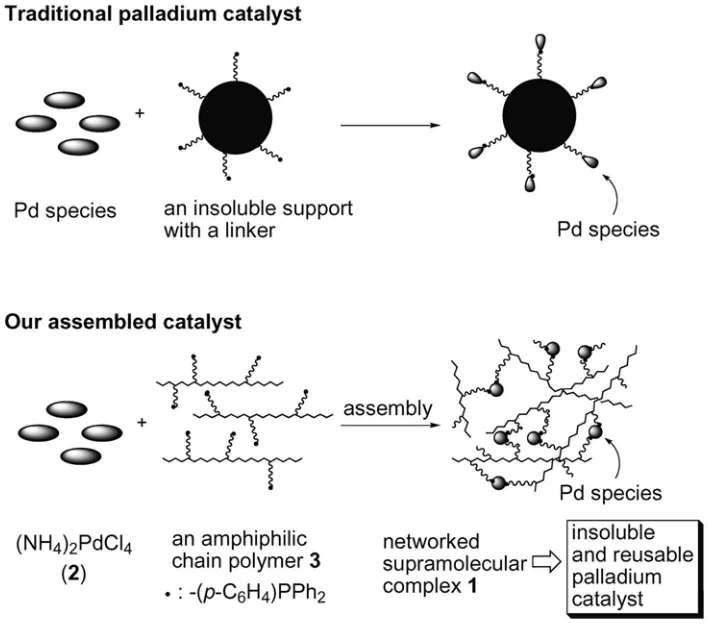
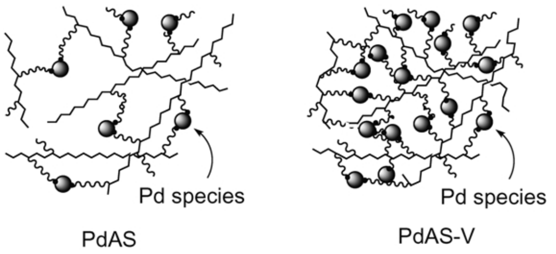


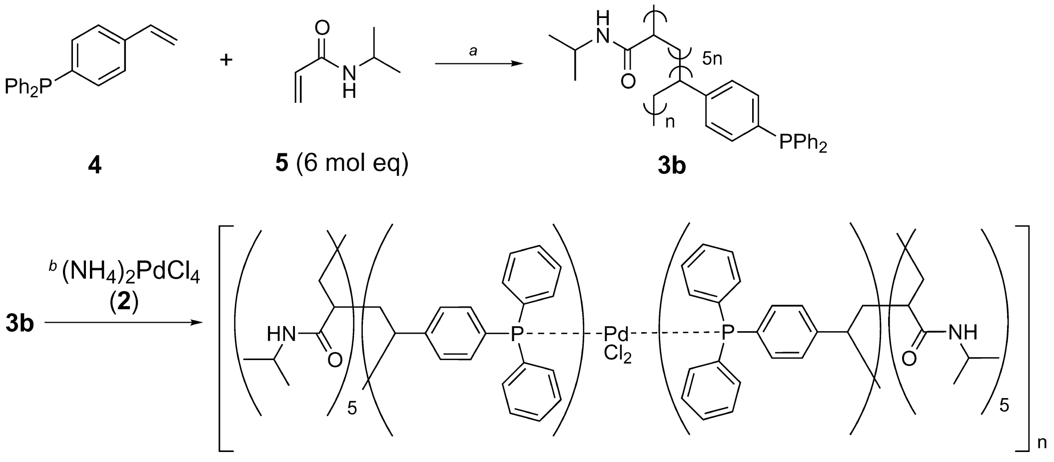
Scheme 1. Concept for the preparation of an assembled catalyst of palladium and non-cross-linked amphiphilic polymer.

challenging than that for the Suzuki–Miyaura reaction. These catalysts were less stable under the Heck reaction condition, and thus often decompose physically or chemically.[4a,b] For example, resulting salts accumulated in the reaction lead to degradation of the catalytic system and choke of catalysts under the Heck conditions. Besides, the reductive elimination of phosphonium cation causes depletion of phosphine-containing palladium catalysts.



Scheme 2. Working model of PdAS and PdAS-V.

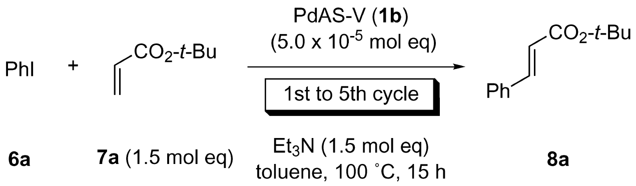
While a preliminary investigation by using PdAS was carried out, it was concluded that PdAS was not so effective owing to its pulverization under the recycled condition of the Heck reaction. We supposed that cross-linking in PdAS was not sufficient to preserve physical strength for the Heck reaction. This hypothesis struck us that a more cross-linked palladium catalyst should enhance the physical strength and the stability. Based on our working hypothesis, we have reported a reformed palladium solid-phase catalyst PdAS-V (**1b**) and partial results on the Heck reaction in toluene.[3e] In this article, we report here the full detail of the development of PdAS-V and a highly efficient and recyclable system for the heterogeneous Heck reaction.[6,7] This time, it is found that PdAS-V showed good stability not only in toluene but



PdAS-V (**1b**)

Scheme 3. Preparation of assembled palladium catalyst PdAS-V. (a) AIBN (2.2 mol %), *t*-BuOH, 75 °C, 41 h, 82%; (b) (1) $(NH_4)_2PdCl_4$ (1 mol equiv.), **3b** (3 mol equiv. as PPh_2 unit), THF–H_2O, rt, 62 h, (2) added H_2O, (3) distilled with Dean–Stark equipment at 80 °C, (4) washed with H_2O, THF, and H_2O successively at 100 °C, 95%.

Table 1. Recycling of PdAS-V for the Heck reaction



Entry	Cycle	Yield (%)	TON	TOF (h^{-1})
1	1st cycle	92	18,400	1230
2	2nd cycle	93	18,600	1240
3	3rd cycle	95	19,000	1270
4	4th cycle	94	18,800	1250
5	5th cycle	95	19,000	1270
	A total TON	94,000	Av. TOF	1250

also in water, and thus both solvents were suitable for this reaction of versatile substrates such as alkylacrylates, styrenes, and acrylic acid with aryl iodides. It is noteworthy that employment of 8.0×10^{-7}–5.0×10^{-5} mol equiv. of PdAS-V facilitated the recycled system of the Heck reaction with the turnover number (TON (=mol of product/mol of catalyst)) up to 1,150,000 and the turnover frequency (TOF (h^{-1})=the turnover number per an hour) up to 12,000 h^{-1}. PdAS-V was reused five times without any decrease in its activity. Furthermore, the efficient synthesis of resveratrol, a promising COX-II inhibitor, was achieved via the PdAS-V-promoted Heck reaction.

2. Results and discussions

2.1. Preparation of PdAS-V

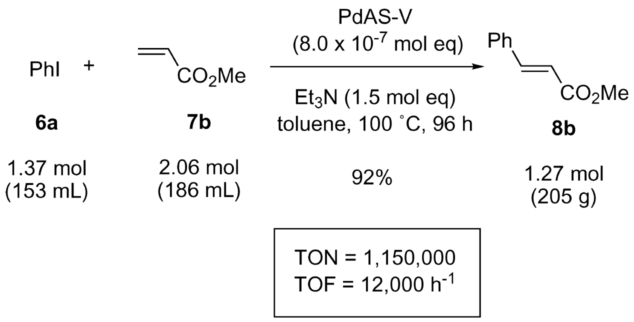
The difference of PdAS-V and PdAS was that the ratio of the *N*-isopropylacrylamide unit to the phosphine unit was 5/1 in PdAS-V while that in PdAS was 10/1.[7] Theoretically, the polymers in PdAS-V were cross-linked eight-fold more than those in PdAS per unit volume, and thus the amount of palladium in PdAS-V increased eight-fold over PdAS per unit content (Scheme 2). This implied that physical strength of PdAS-V was superior to that of PdAS, so that PdAS-V was expected to be prevented from pulverization under the Heck reaction conditions.

The reformed catalyst PdAS-V was prepared from **2** and **3b** using the method for the preparation of PdAS as shown in Scheme 3.[3c] Random copolymerization of 4-diphenylstyrylphosphine (**4**) with 6 mol equiv. of *N*-isopropylacrylamide (**5**) in the presence of 2.2 mol% of AIBN gave **3b** in 82% yield. The gel permeation chromatography showed that the molecular weight of **3b** was wide-ranging (approximately 5000–70,000). The ratio of the phosphine to the amide units in **3b** was determined by ^{1}H NMR measurements in $CDCl_3$ to be 1/5, and the phosphine unit was hardly oxidized in this polymerization as shown by ^{31}P NMR. This ratio of the phosphine to the amine unit as 1/5 was found to be reproducible in several lots. Thus, PdAS-V (**1b**) was prepared by self-assembly of **2** and **3b** (3 mol equiv. in phosphine) in THF and H_2O, resulting in the formation of precipitates. After the suspension was washed to remove a trace amount of unreacted palladium species and polymers, PdAS-V was obtained in 95% yield. It was a dark reddish solid that was insoluble in water, methanol, DMF, ethyl acetate, dichloromethane, THF and toluene as well as was PdAS, whereas polymer **3b** was soluble in organic solvents such as $CHCl_3$, CH_2Cl_2 and THF. Gel-phase ^{31}P NMR of PdAS-V showed the similar broad signals at 26.1 and 32.5 ppm as that of PdAS, which must be assigned as the peak of $PdCl_2(PPh_2Ar)_2$ and $ArPh_2P{=}O$, respectively. These results indicated that the structure of PdAS-V was analogous to that of PdAS, and thus the self-assembly process of **3b** and **2** to form the cross-linked and supramolecular complex was successful.

2.2. The catalytic activity of PdAS-V

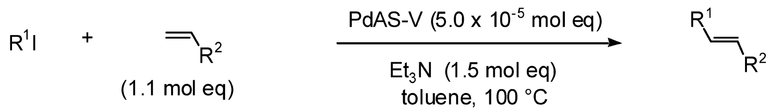
To check the potency of PdAS-V for the Heck reaction, PdAS-V was treated with the reaction of **6a** with 1.5 mol equiv. of **7a** in the presence of Et_3N in toluene at 100 °C (Table 1). The results agreed with our working hypothesis that PdAS-V was a highly active and reusable catalyst; the employment of 5.0×10^{-5} mol equiv. of PdAS-V in the 5th cycled run afforded **8a** in 95% yield with TON being 19,000 (entry 5).[8] PdAS-V was recycled five times without any loss of its activity. The average yield of five runs was 94%. A total turnover number of PdAS-V in the 1st to the 5th cycled runs was 94,000, and the average of TOF was 1250.

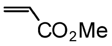
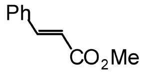
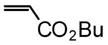
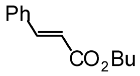
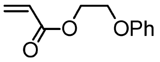
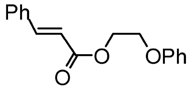
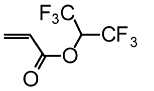
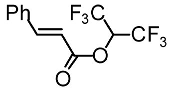
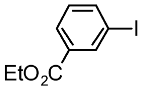
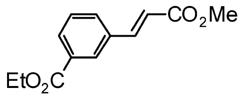
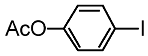
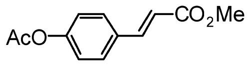
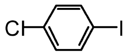
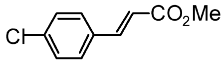
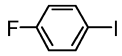
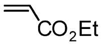
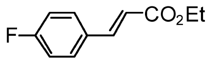
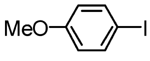
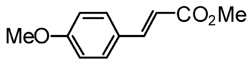
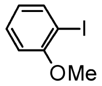
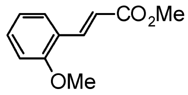
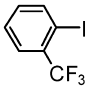
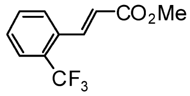
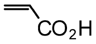
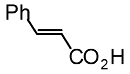
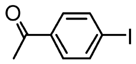
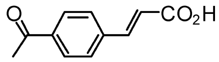
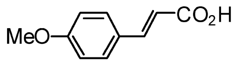
Since the recycled ability and high TON of PdAS-V was achieved in the Heck reaction, we further investigate the



Scheme 4. The heterogeneous Heck reaction catalyzed by 8×10^{-7} mol equiv. of PdAS-V. (a) The product **8b** was purified by crystallization.

Table 2. The Heck reaction of aryl iodides **6** with acrylates **7** and **9**



Entry	R^1I				Time (h)	Product	Yield
1	**6a**			**7b**	12		**8b**:93%
2	**6a**			**7c**	20		**8c**:98%
3	**6a**			**7d**	20		**8d**:97%
4	**6a**			**7e**	5		**8e**:95%
5		**6b**	**7b**		20		**8f**:95%
6		**6c**	**7b**		20		**8g**:92%
7		**6d**	**7b**		20		**8h**:95%
8		**6e**		**7f**	20		**8i**:93%
9		**6f**	**7b**		20		**8j**:92%
10		**6g**	**7b**		40		**8k**:90%
11		**6h**	**7b**		60		**8l**:82%
12	**6a**			**9**	5		**10a**:93%[a]
13		**6i**	**9**		4		**10b**:90%[a]
14	**6f**		**9**		8		**10c**:87%[a]

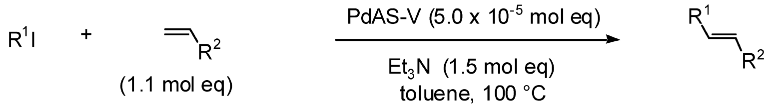
[a] The product was purified by recrystallization without column chromatography.

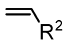
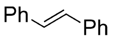
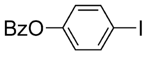
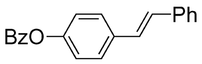
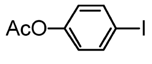
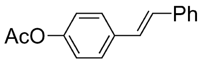
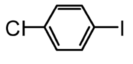
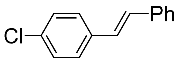
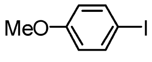
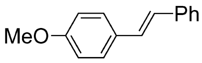
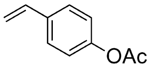
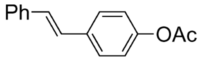
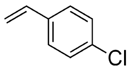
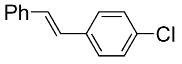
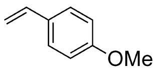
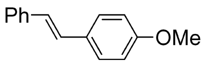
limitation of its catalytic activity. It was found that less than 1 ppm mol equiv. of PdAS-V catalyzed the coupling efficiently as shown in Scheme 4. The employment of 8×10^{-7} mol equiv. of PdAS-V in the coupling of **6a** (1.37 mol; 153 mL) with **7b** (2.06 mol; 186 mL) for 96 h provided **8b** (1.27 mol; 205 g) in 92% yield, isolated by crystallization. It is notable that PdAS-V promoted the reaction on a scale of more than 1 mol with TON and TOF in its reaction reaching 1,150,000 and 12,000 h^{-1}, respectively. That is, PdAS-V was the most active solid-phase catalyst for the Heck reaction. As far as we know, this is the highest TON value by the reusable catalysts for the Heck reaction.

2.3. The Heck reaction of aryl iodides with acrylates in toluene

In order to establish the scope of the sequence as depicted in Table 2, the coupling of various aryl halides with acrylates was investigated. All the reactions in Table 2 were performed under identical conditions as in Table 1: aryl iodide **6** (1 mol equiv.), alkene **7** (1.5 mol equiv.), PdAS-V

Table 3. The Heck reaction of aryl iodides **6** with styrenes **11**



Entry	R¹I				Time (h)	Product	Yield
1	**6a**			**11a**	12		**12a**:90%
2		**6j**	**11a**		20		**12b**:86%[a]
3		**6c**	**11a**		20		**12c**:75%[a]
4		**6d**	**11a**		20		**12d**:87%[a]
5		**6f**	**11a**		20		**12e**:92%[a]
6	**6a**			**11b**	20		**12c**:95%[a]
7	**6a**			**11c**	20		**12d**:88%[a]
8	**6a**			**11d**	20		**12e**:93%[a]

[a] These products were purified by recrystallization without column chromatography.

(5.0×10^{-5} mol equiv.), Et_3N (1.5 mol equiv.) in toluene at 100 °C. Full conversions were achieved for these couplings in the presence of PdAS-V to afford cinnamic esters in high yields with TON and TOF of PdAS-V reached approximately 20,000 and 1000 h^{-1}, respectively. The reaction of **6a** with alkylacrylates **7b–e** proceeded in 5–20 h to give the corresponding couplings in 93–98% yields (entries 1–4). It is notable that the coupling of hexafluoroisopropyl acrylate (**7e**), an electron-deficient olefin, proceeded much faster and completed in 5 h to furnish **8e** in 95% yield (entry 4). Electron-deficient aryl iodides such as ethoxycarbonyl-, acetoxy-, chloro-, and fluoro-substituted iodobenzenes were also converted to **8f–i** in more than 90% yields (entries 5–8). The reaction system was applicable to the reaction of an electron-rich iodoarene (entry 9). Moreover, the coupling of *ortho*-substituted aryl iodides, sterically hindered substrate, proceeded to afford the corresponding products in high yields while it was slower (entries 10–11). Interestingly, the reactions of acrylic acid (**9**) in toluene were faster than that of alkyl acrylates to afford cinnamic acids **10a** and **10b** in 93 and 90% yields (Table 2).

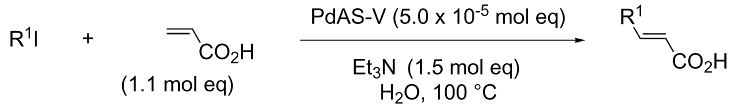
2.4. The Heck reaction of aryl iodides with styrenes in toluene

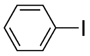
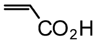
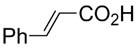
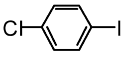
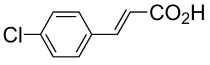
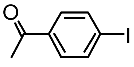
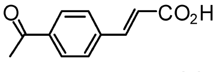
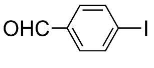
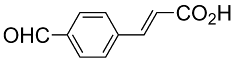
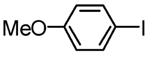
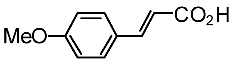
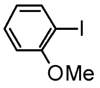
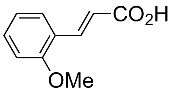
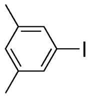
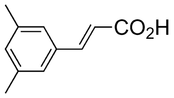
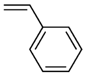
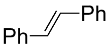
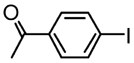
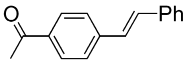
PdAS-V was applicable to the coupling of styrene derivatives **11**. The reaction conditions were identical with that in the reaction of acrylates. Aryl iodides with styrenes were also converted smoothly to the corresponding stilbenes in high yields with TON and TON being approximately 20,000 and 1000 h^{-1}. The reaction of iodobenzene (**6a**) with styrene (**11a**) was carried out, stilbene (**12a**) was obtained in 90% yield. Both electron-deficient (entries 2–4) and -donating (entry 5) aryl iodides were efficiently coupled with **11a** to provided the corresponding coupling products **12b–12e** in high yields. Besides, the electron-deficient and -donating styrenes **11b–d** were also useful reactants to give **12c–e** in approximately 90% yields (entries 6–8) (Table 3).

2.5. The Heck reaction in water

All the reactions above mentioned were performed in toluene. Since PdAS-V was composed of an amphiphilic polymer, it was expected that PdAS-V was also stable and works in water. Water is inexpensive, nontoxic, nonflammable, and easily available solvent. It nowadays receives much attention as a reaction solvent, although it has not been commonly used because palladium catalysts were generally unstable in water and hydrophobic substrates were insoluble in water.[8] Thus, the heterogeneous Heck reaction in water was investigated as shown in Table 4.[9] We were fueled by finding that PdAS-V has a good stability and activity even in water. The coupling of **6a** with acrylic acid (**9**) proceeded smoothly in 6 h to result in the formation of cinnamic acid (**10a**) in 94% yield (entry 1). Substituted aryl iodides including an *ortho*-substituted aryl iodide were also appropriate substrates in these couplings (entries 2–7). It was notable that styrene (**11a**) was also a useful reactant in water while both aryl iodides and styrene was not dissolved in water (entries 8 and 9). This result suggested that dispersion of reagents in water might be effective for promoting the reaction. Furthermore, it should be noted that

Table 4. The Heck reaction in water



Entry	R^1I				Time (h)	Product	Yield[a]
1		**6a**		**9**	6		**10a**:94%
2		**6d**	**9**		6		**10d**:91%
3		**6i**	**9**		4		**10b**:91%
4		**6k**	**9**		6		**10e**:94%
5		**6f**	**9**		24		**10c**:88%
6		**6g**	**9**		24		**10f**:95%
7		**6h**	**9**		8		**10g**:92%
8	**6a**			**11a**	36		**12a**:76%
9		**6i**	**11a**		30		**12f**:97%

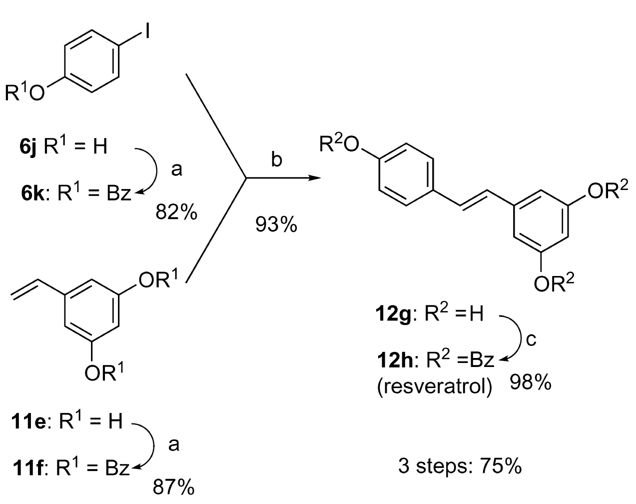
[a] These products were purified by recrystallization without column chromatography.

any catalytic activity in the reaction filtrate could not be observed, indicating obviously non-leaching of the metal catalyst from PdAS-V even in the reactions in water.

2.6. Efficient synthesis of resveratrol via the Heck reaction by PdAS-V

To demonstrate the utility of PdAS-V for the synthesis of bioactive compounds, resveratrol (**12h**) was synthesized via the heterogeneous Heck reaction. Resveratrol is a new type antitumor agent that can inhibit all three stages of cancer by inducing quinone reductase activity, inhibiting cyclooxygenase-2 (COX-2), and inducing the expression of nitroblue tetazolium reduction activity. Furthermore, it can inhibit the development of cardiovasacular disease through its ability as an antioxidant to inhibit platelet aggregation and eicosanoid synthesis and its ability to modulate lipoprotein metabolism.[10] However, it is isolated from natural sources in trace amounts,[10d] so that efficient chemical syntheses of **12h** are required.[11,12] The starting materials 4-iodophenol (**6j**) and 3,5-dihydroxystyrene (**11e**)[13] were protected by benzoyl group to afford **6k** and **11f** in 82 and 87% yield, respectively. The heterogeneous Heck reaction[12] of aryl iodide **6k** and alkene **11f** proceeded smoothly in the presence of PdAS-V to furnish the coupling **12g** in 93% yield. Deprotection of **12g** over NaOMe in THF and MeOH provided resveratrol (**12h**) in 98% yield. The total yield of resveratrol from commercially available **6j** was 75% in 3 steps (Scheme 5).

In conclusion, we have developed a new insoluble and reusable catalyst PdAS-V prepared from self-assembly of



Scheme 5. Efficient synthesis of resveratrol via the Heck reaction by PdAS-V. Reagents and conditions: (a) BzCl, pyridine, CH_2Cl_2, 0 °C; (b) **6k** (1 mol equiv.), **11f** (1.5 mol equiv.), PdAS-V (5×10^{-4} mol equiv.), Et_3N (1.5 mol equiv.), toluene, 100 °C, 12 h; (c) NaOMe, THF–MeOH, 50 °C, 5 h.

$(NH_4)_2PdCl_4$ (**2**) and non-cross-linked amphiphilic phosphine polymer **3b**. The heterogeneous Heck reaction using PdAS-V afforded the corresponding couplings in high yields with TON up to 1,150,000. Using only 5×10^{-5} mol equiv., PdAS-V was reused up to five times while still retaining its activity. PdAS-V was stable in toluene and water, so that it efficiently catalyzed the Heck reaction in these media. Resveratrol was synthesized via the Heck reaction by PdAS-V.

3. Experimental

3.1. General

All the products were isolated, and hence all the yields presented meant isolated yields. Melting points were uncorrected. ^1H and ^{13}C NMR spectra were recorded with 400 and 600 MHz (^1H NMR) pulse Fourier transform NMR spectrometers in $CDCl_3$ solution with tetramethylsilane as an internal standard. Gel-phase ^{31}P NMR spectra were recorded with a 600 MHz (^1H NMR) pulse Fourier transform NMR spectrometers in $CDCl_3$ suspension with 85% H_3PO_4 aqueous solution as an external standard. All the reactions were performed under an argon atmosphere unless cited.

3.2. Materials

Toluene was distilled from CaH_2 prior to use. Purchased aryl iodides, acrylates, styrenes, and triethyl amine were purified by distillation. *N*-isopropylacrylamide (purchased from Aldrich), AIBN, *t*-BuOH, and $(NH_4)_2PdCl_4$, were used without purification.

3.2.1. Poly[(*N*-isopropylacrylamide)$_5$-*co*-(4-diphenylphosphinostyrene)] (3b). To a solution of **4** (4.65 mmol) in *t*-BuOH (50 mL), after treatment of ultrasonication for 20 min at 60 °C to degass and dissolve **4** in *t*-BuOH, was added **5** (27.8 mmol) at rt, and the mixture was degassed by ultrasonication for 20 min. To the solution was added AIBN (0.10 mmol), and the resulting solution was again degassed by ultrasonication for 2×25 min, stirred at 75 °C for 41 h, and evaporated at 80 °C to give a crude polymer. It was purified by precipitation (×3) from CH_2Cl_2 (10 mL) and Et_2O (150 mL), dried in vacuo (ca. 0.08 mm Hg) to afford **3b** in 82% yield: IR (KBr, cm^{-1}): ν 3306, 2971, 2934, 1653, 1539, 1460, 747, 698; ^1H NMR (400 MHz, $CDCl_3$ with a trace of D_2O): δ 1.12 (br, 60H), 1.64–1.78 (br, 20H), 2.10 (br, 10H), 3.98 (br, 10H), 7.00–7.64 (br, 28H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.6, 41.3, 42.4, 128.3, 128.5, 133.4, 133.6, 174.2; ^{31}P NMR (243 MHz, $CDCl_3$): δ −3.0 (br, Ar_2PhP). Anal. Calcd for $C_{50n}H_{74n}O_{6n}N_{5n}P_n$ as $\mathbf{2}\cdot 1nH_2O$: C 68.861%, H 8.550%, N 8.030%, found: C 68.207%, H 8.975%, N 8.395%.

3.2.2. Poly{dichlorobis[(*N*-isopropylacrylamide)$_5$-*co*-(4-diphenylstyrylphosphine)]palladium} (PdAS-V) (1b). All solvents were degassed by ultrasonication and argon substitution prior to use. To a well-stirred solution of **3b** (307 mg; 0.36 mmol in phosphine) in THF (72 mL) was added a solution of **2** (34.1 mg; 0.12 mmol) in H_2O (30 mL), and the mixture was again degassed. After the mixture stirred for 62 h at room temperature, a yellow precipitate was formed. Water (30 mL) was added to the suspension, and THF was removed at 80 °C for 4 h with Dean–Stark equipment to give a reddish precipitate. This precipitate was stirred at 100 °C successively in H_2O (100 mL) for 12 h, in THF (100 mL) for 3 h and in H_2O (100 mL) for 12 h to wash the unreacted palladium species and polymers. After drying in vacuo (ca. 0.08 mm Hg), a dark red solid **3** was obtained in almost quantitative yield: IR (KBr, cm^{-1}): ν 2971, 2934, 1651, 1537, 1460, 694; gel-phase ^1H NMR (600 MHz, $CDCl_3$): δ 1.06 (br, 60H), 1.54–2.10 (br, 30H), 3.68 (10H), 6.56–7.47 (br, 24H); gel-phase ^{13}C NMR (150 MHz, $CDCl_3$): δ 22.6, 41.3, 128.0, 174.1; gel-phase ^{31}P NMR (243 MHz, $CDCl_3$) 26.1 (br), 32.1 (br). Anal. Calcd for $C_{150n}H_{234n}O_{24n}N_{15n}P_3Pd_{1n}Cl_{2n}$ as $PdAS\cdot 9nH_2O$: C 62.090%; H 8.123%, N 7.240%, found: C 60.956%; H 8.445%, N 8.304%.

3.2.3. Recycle of PdAS-V for the Heck reaction (general procedure for the Heck reaction catalyzed by PdAS-V in toluene) (Table 1). The mixture of **6a** (4.1 mL; 36.5 mmol), **7a** (8.0 mL; 54.7 mmol), Et_3N (7.6 mL; 54.7 mmol) in toluene (18 mL) was degassed by untrasonication for 30 min. The solution was added to PdAS-V (5 mg; 1.82 μmol), and the resulting suspension was stirred at 100 °C for 15 h. After the reaction mixture was cooled to room temperature, methanol was added to the mixture, and the resulting solution with insoluble PdAS-V was filtered. At that time, PdAS-V was recovered on the filter. The filtrate was evaporated and it was diluted with EtOAc and water. The two-phase solution was extracted with EtOAc, washed with water and brine, dried over $MgSO_4$. The residue was purified by column chromatography or recrystallization (toluene–EtOH) to give **8a** in 82–95% yields. The recovered PdAS-V was dried in vacuo and reused.

3.2.4. Hexafluoropropyl cinnamate (8e). IR (KBr, cm^{-1}): ν 3088, 3034, 2971, 1748, 1636, 766, 691; ^1H NMR (400 MHz, $CDCl_3$): δ 5.83 (hept, J=2.9 Hz, 1H)), 6.38 (d, J=15.8 Hz, 1H), 7.25–7.34 (m, 3H), 7.42–7.45 (m, 2H), 7.75 (d, J=15.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): 66.6, 114.1–124.8 (m), 114.8, 128.5, 128.9, 131.3, 133.4, 149.1, 163.2; MS(EI): *m*/*z* 298 (M^+), 131, 103, 77; HR-MS (EI): calcd for $C_{12}H_8F_6O_2$ 298.0428, found 298.0423.

3.3. Synthesis of resveratrol

3.3.1. 3,5-Dibenzoyloxystyrene (11f). To a solution of 3,5-dihydroxystyrene (**11e**) (408 mg; 3.0 mmol) was added pyridine (1.21 mL; 15.0 mmol) and benzoyl chloride (1.04 mL; 9.0 mmol) at 0 °C. After the resulting solution was stirred for 1.5 h, water was added. The two-phase solution was extracted with CH_2Cl_2, washed with water and brine, dried over $MgSO_4$, and purified by column chromatography to give **11f** in 87% yield (898 mg; 2.61 mmol). IR (KBr, cm^{-1}): ν 3071, 2988, 1732, 1590; ^1H NMR (400 MHz, $CDCl_3$): δ 5.36 (d, J=11.0 Hz, 1H)), 5.80 (d, J=17.6 Hz, 1H), 6.72 (dd, J=11.0, 17.6 Hz, 1H), 7.10–7.11 (m, 1H), 7.21–7.22 (m, 2H), 7.54–7.55 (m, 4H), 7.63–7.67 (m, 2H), 8.20–8.22 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 114.9, 115.9, 116.9, 128.5, 129.1, 130.1, 133.6, 135.2, 139.9, 151.4, 164.5; MS(EI): *m/z* 344 (M^+), 105, 77; HR-MS (EI): Calcd for $C_{22}H_{16}O_4$ 344.1049, found 344.1055.

3.3.2. (*E*)-3,5,4′-Tribenzoyloxystyrene (12g) (the Heck reaction by PdAS-V). The mixture of **6k** (251 mg; 0.774 mmol), **11f** (400 mg; 1.16 mmol), Et_3N (0.162 mL; 1.16 mmol) in toluene (0.39 mL) was degassed by untrasonication for 30 min. The solution was added to PdAS-V (1.1 mg; 0.387 μmol), and the resulting suspension was stirred at 100 °C for 12 h. After the reaction mixture was cooled to room temperature and was filtered with EtOAc and water, the filtrate was washed with water and brine, dried over $MgSO_4$, and purified by column chromatography (eluent: hexane) to afford (*E*)-3,5,4′-tribenzoyloxystyrene (**12g**) in 93% yield (390 mg; 0.72 mmol). IR (KBr, cm^{-1}): ν 3061, 3034, 1738, 1599; ^1H NMR (400 MHz, $CDCl_3$): δ 7.06 (d, J=16.1 Hz, 1H)), 7.10–7.11 (m, 1H), 7.15 (d, J=16.1 Hz, 1H), 7.21–7.24 (m, 2H), 7.32–7.32 (m, 2H), 7.48–7.56 (m, 8H), 7.61–7.66 (m, 3H), 8.19–8.23 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 114.7, 117.1, 121.9, 127.1, 127.6, 128.4, 128.5, 129.1, 129.3, 129.6, 130.0, 130.1, 133.5, 133.6, 134.4, 139.6, 150.5, 151.5, 164.6, 164.8; MS(EI): *m/z* 540 (M^+), 105, 77; HR-MS (EI): Calcd for $C_{35}H_{24}O_6$ 540.1573, found 540.1570.

3.3.3. Resveratrol (12h). The solution of **12g** THF–MeOH was stirred at 50 °C for 5 h. After the mixture was cooled to rt, EtOAc and water was added. The two-phase solution was extracted with EtOAc, washed with water and brine, dried over $MgSO_4$, purified by column chromatography to afford resveratrol (**12h**) in 98% yield (22.4 mg; 0.098 mmol).

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