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Recyclable Hybrid Silica-Based Catalysts Derived from Pd–NHC Complexes for Suzuki, Heck and Sonogashira Reactions

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Two silylated Pd–NHC complexes were immobilized on hybrid silicas by sol-gel cocondensation with tetraethyl orthosilicate (TEOS) and performed well as recyclable catalysts towards the Heck, Suzuki, and Sonogashira coupling reactions. Remarkable conversion and recyclability were achieved in the Suzuki reaction with a challenging aryl chloride. No side products and no undesired homocoupling were observed in Suzuki or Heck reactions, which facilitates the final purification step for the cross-coupling products. High turnover numbers and turnover frequencies were found for copper- and phosphane-free Sonogashira reaction between *p*-bromoacetophenone and phenylacetylene.

Introduction

Palladium-catalyzed carbon–carbon bond forming reactions such as the Suzuki–Miyaura,[1] Heck,[2] and Sonogashira[3] coupling reactions are important synthetic transformations that are widely employed for the preparation of a great variety of complex organic molecules and materials such as natural products, fine chemicals, drugs, agrochemicals, and polymers.[4] However, these Pd-catalyzed reactions suffer from the high cost of this metal. Furthermore, Pd traces are undesired in the final pharmaceutically active compounds. Therefore, the efficient recovery and recycling of the catalyst remains a scientific challenge of economic and environmental relevance. For these reasons, the immobilization of homogeneous palladium catalytic systems is the subject of intense research.[2d,5] Other challenges facing this field are the design of catalysts that are more robust and efficient with higher turnover numbers (TON) and turnover frequencies (TOF),[6] as well as expanding the search for catalytic systems that are capable of activating aryl chlorides,[7] which are substrates that are significantly less reactive but also less expensive than the corresponding aryl bromides or iodides.

Palladium complexes incorporating Arduengo-type *N*-heterocyclic carbenes (NHC)[8] appear to be efficient systems with which to achieve these goals. In some cases they are formed in situ from the corresponding imidazolium salt and a common palladium source;[9] however, this approach has the drawback of requiring an excess of expensive ligands, which then need be removed from the reaction mixture. Alternatively, well-defined monoligated Pd^{II}–NHC precatalysts[10] have been synthesized that showed higher levels of activity. However, they sometimes require multistep syntheses and/or rigorously anhydrous and inert conditions even if the intermediate carbene ligand is not isolated. Recently, these drawbacks have been overcome to some extent with the development of processes for the facile preparation of air and moisture stable Pd–NHC precatalysts, without the need to generate the free carbene, using readily available starting materials on a large scale. Nolan's group has reported the synthesis of [Pd(acac)Cl(NHC)] complexes from $[Pd(acac)_2]$ and the corresponding imidazolium chloride, which have proven to be highly efficient in the Buchwald–Hartwig amination and in α-ketone arylation with aryl bromides and chlorides.[11] Organ and collaborators have synthesized $[PdCl_2(3\text{-}ClPyr)(NHC)]$ complexes from $PdCl_2$, 3-chloropyridine, and the corresponding imidazolium salt by direct C–H insertion. Furthermore, they have demonstrated that such complexes perform well when aryl bromides and chlorides are employed in Suzuki–Miyaura and Negishi cross-coupling reactions, and in Pd-catalyzed amination. The 3-chloropyridine plays the role of a throw-away ligand (PEPPSI-type complexes: **p**yridine-**e**nhanced **p**recatalyst **p**reparation, **s**tabilization and **i**nitiation).[12] To the best of our knowledge, to date, no Heck or Sonogashira reactions have been described that use these monoligated Pd–NHC complexes.

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Some of us have previously described several silica-supported phosphane-free palladium catalytic systems either by applying sol-gel processes or grafting methods. Whereas macrocyclic triolefinic Pd^0 complexes covalently anchored to the silica matrix were active and recyclable catalysts for Suzuki coupling only with aryl iodides,[13] hybrid silica materials covalently Si–C bonded to di(2-pyridyl)methylamine-palladium dichloride complex were found to be efficient recyclable catalysts for the Heck and Sonogashira reactions with aryl bromides and for Suzuki–Miyaura couplings with aryl bromides and chlorides.[14] A significant number of publications have appeared in recent years on palladium catalysts based on imidazolium-derived organosilicas for C–C bond forming reactions; however, a successful recyclable catalytic system that is able to operate with less expensive aryl chlorides is still a challenge. Indeed, only few studies exist on Suzuki coupling that describe efficient and reusable supported catalysts for this kind of substrate.[15]

Quite recently, we examined the immobilization of Pd–NHC catalysts by using a sol-gel process. In this case, the hydrolysis–condensation, in the presence of a surfactant, of a bis-silylated precursor derived from a dihydroimidazolium salt was performed in the first step. Catalytic systems composed of the resulting hybrid silica materials and palladium acetate were tested in C–C coupling reactions.[16] Although some activity was found for the Suzuki cross-coupling with an activated aryl chloride and with moderate success in recycling, the conversions remained quite low even under harsh conditions.

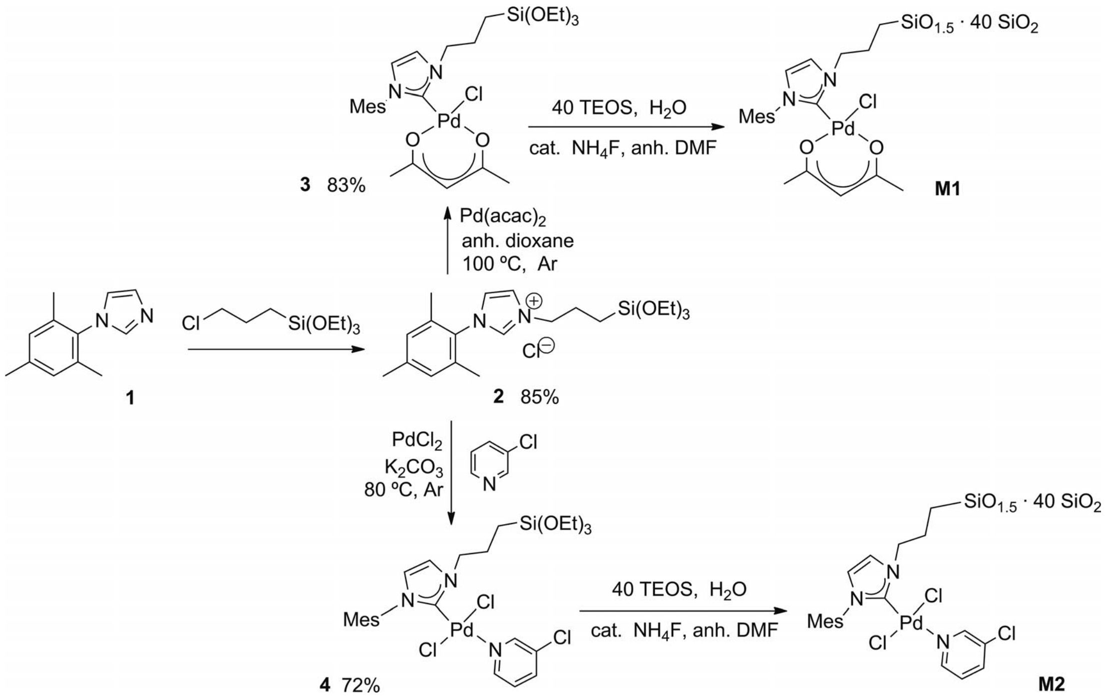
To date, such silica-immobilized Pd–NHC catalysts have mostly been obtained by post-complexation of the preformed hybrid imidazolium or dihydroimidazolium derived silica.[15] We describe herein the preparation of organic–inorganic hybrid silica materials derived from monosilylated [Pd(acac)Cl(NHC)] and [PdCl$_2$(3-ClPyr)(NHC)] complexes by applying a sol-gel process. In this case, the Pd–NHC complex is generated at the organosilane precursor step, which is then subjected to the sol-gel hydrolysis step to form the immobilized Pd–NHC catalysts. Their activity and reusability were then inspected in the Suzuki, Heck, and Sonogashira reactions.

Results and Discussion

Monomer Synthesis and Preparation of Supported Catalysts

Syntheses of the monosilylated imidazolium salt **2**, the monocarbenic Pd–NHC complexes **3** and **4**, and the hybrid silica materials **M1** and **M2** derived thereof, are summarized in Scheme 1. Chloride **2** was obtained by heating a mixture of 1-mesitylimidazole **1**[17] and (3-chloropropyl)triethoxysilane under argon at 90 °C for five days under solvent-free conditions.[18] Palladium complex **3** was prepared by treatment of [Pd(acac)$_2$] with a slight excess of the monosilylated salt **2** in anhydrous dioxane at 100 °C under argon for 20 h.[11a] Pure **3** was obtained in 83% isolated yield. On the other hand, monosilylated salt **2** was reacted under argon with palladium(II) chloride and excess 3-chloropyridine at 80 °C overnight in the presence of potassium carbonate,[12a] to afford complex **4** in 72% isolated yield.

Complex **3** was characterized by NMR and HRMS analyses. A complete chemical shift assignment was made on the basis of two-dimensional NMR experiments (^{1}H-^{1}H COSY, ^{1}H-^{1}H NOESY, ^{1}H-^{13}C HSQC, ^{1}H-^{13}C HMBC). Three different methyl and two aromatic signals belonging



Scheme 1. Synthesis of hybrid silica materials **M1** and **M2**.

to the mesityl ring were observed in the ^{1}H NMR spectrum of complex **3**. On the other hand, the methylene group attached to the second nitrogen atom of the NHC ligand appeared as two diastereotopic multiplets centered at $\delta = 4.4$ and 5.0 ppm. The ^{1}H-^{1}H NOESY spectrum of **3** presented strong chemical exchange cross-peaks for all these signals (the two *ortho* methyl groups, the two aromatic protons and the diastereotopic methylene group), indicating restricted rotation around the N–Mes and N–CH_2 bonds (see the Supporting Information, Figures S1 and S2).

The PEPPSI-type complex **4** also deserves some comments. To ensure complete removal of the excess of 3-chloropyridine, vacuum distillation of this solvent was performed followed by thorough washing of the residue with anhydrous pentane and careful drying of the insoluble remaining solid under vacuum. Although the results obtained from elemental analysis showed that **4** was pure, the corresponding ^{1}H NMR spectrum was complex and showed more peaks than expected. Three different points must be commented. First, in the ^{1}H NMR spectrum of **4** (see the Supporting Information, Figure S3) two sets of signals in equilibrium were observed for 3-chloropyridine subunits, one of which corresponded to the free ligand and the second due to the coordinated ligand. This was confirmed by a ^{1}H-^{1}H NOESY experiment (see the Supporting Information, Figure S4) in which chemical exchange cross-signals were observed. For instance, the signals at $\delta = 8.59$ and 8.85 ppm would correspond to the same H-2 proton of the 3-chloropyridine ring but in a different chemical environment. Secondly, two different triplets at $\delta = 4.74$ and 4.80 ppm, with a relative proportion of 1:0.25, were also observed, corresponding to the protons of the methylene group attached to the nitrogen atom of the NHC ligand for two different palladium complex species. Analogous duplicity of signals was also observed for the triethoxysilyl group (superimposed methylene and methyl signals of the ethoxy group centered at $\delta = 3.86$ and 1.25 ppm, respectively). The rotation around the N–Mes bond was not restricted at room temperature in this case, and both *ortho* methyl groups appeared as a singlet at $\delta = 2.2$ ppm, whereas the *para* methyl group presented a signal at $\delta = 2.3$ ppm. As a third point, the spectrum showed additional broad signals that were probably due to other palladium species derived from the decoordination of 3-chloropyridine. Although different spectra were recorded at lower temperature (273 and 250 K), no further information could be obtained for this unknown species due to the fact that the signals remained broad.

From this study we concluded that palladium complex **4** exists as a mixture of two isomeric structures, one of which predominates. Moreover, the complex was in equilibrium with free 3-chloropyridine ligand (see the Supporting Information, Figures S3 and S4) and a third, unknown, palladium species with higher molecular size was also present. Although the nature of the minor palladium species resulting from decoordination of the pyridine ligand from complex **4** could not be determined (variable-temperature ^{1}H NMR studies did not provide useful information), a dimeric complex with two bridging chloro ligands could be envisaged. This should be in accordance with DOSY experiments (see the Supporting Information, Figure S4) in which we observed two species of similar molecular weight (corresponding to the two isomeric forms for **4**), a species of higher molecular weight (the dimer), and a species of lower molecular weight (the 3-chloropyridine).

Palladium-containing hybrid silica materials **M1** and **M2** were obtained by standard cogelification of the corresponding precursors with tetraethyl orthosilicate (TEOS) (40:1 molar ratio of TEOS to **3** or **4**) in dimethylformamide, using a stoichiometric amount of water with respect to the ethoxy groups, and ammonium fluoride as catalyst (1 mol-% with respect to silicon) (Scheme 1). Standard nucleophilic fluoride catalysis was considered appropriate for the sol-gel cogelification because it avoids the acidic or basic medium required for alternative acid or basic catalysis, which may be detrimental to the coordinated complex. The materials were characterized by solid-state ^{29}Si NMR spectroscopic analysis, N_2-sorption measurements, and elemental analysis; the amount of palladium was also determined by inductively coupled plasma (ICP) analysis (Table 1). The presence of the organic ligand in the hybrid materials was confirmed by solid state ^{29}Si NMR analysis, which showed two sets of chemical shifts: T units at around $\delta = -55$ to -75 ppm, resulting from the hydrolysis–condensation of organosilanes **3** or **4**, and Q units, ranging from $\delta = -90$ to -120 ppm, formed from TEOS, as exemplified by the ^{29}Si NMR solid state spectra of **M1** (Figure 1). The low intensities of the T units with respect to the Q units are due to the high dilution of the organometallic moiety within the silica matrix. The organosilicas present type IV nitrogen sorption isotherms,[19] corresponding to mesoporous materials (Figure 2). In both cases, the contribution of micropores is negligible, most of the pores being in the mesoporous range. Noticeable differences in terms of porosity were observed depending on the precursor used, with the Brunauer–Emmett–Teller (BET) surface areas varying from 730 to 810 $m^2 g^{-1}$ (Table 1). Interestingly, the coordinating ligand (acac or 3-chloropyridine) induces very important textural differences to the resulting materials **M1** and **M2**. A narrow pore size distribution is observed for **M2**, whereas a bi-

Table 1. Analytical and textural data of hybrid silica materials **M1** and **M2**.

M	^{29}Si CP MAS NMR				S_{BET}	Pore	Pore	% Pd	mmol
	T^3	Q^2	Q^3	Q^4	$[m^2 g^{-1}]$	diameter [Å]	volume[a] $[cm^3 g^{-1}]$		Pd/g
M1	–67.6	–92.8	–102.0	–110.9	810	42; 70[b]	0.91	2.77	0.260
M2	–67.0	–92.0	–101.8	–111.5	730	100–120	1.26	2.48	0.233

[a] Adsorbed volume at $p/p^0 = 0.99$. [b] Bimodal distribution.

modal distribution is found for **M1**. Significant differences in pore size were also observed between the materials (Table 1); indeed medium mesopores (42–70 Å) were obtained for **M1**, and large mesopores (100–120 Å) for **M2** with a similar variation of the pore volume (from 0.91 to 1.26 $cm^3 g^{-1}$).

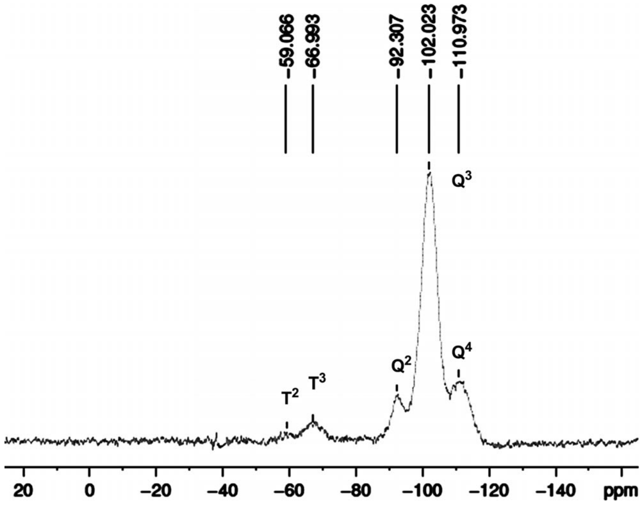


Figure 1. ^{29}Si solid-state CP-MAS NMR spectrum of **M1**.

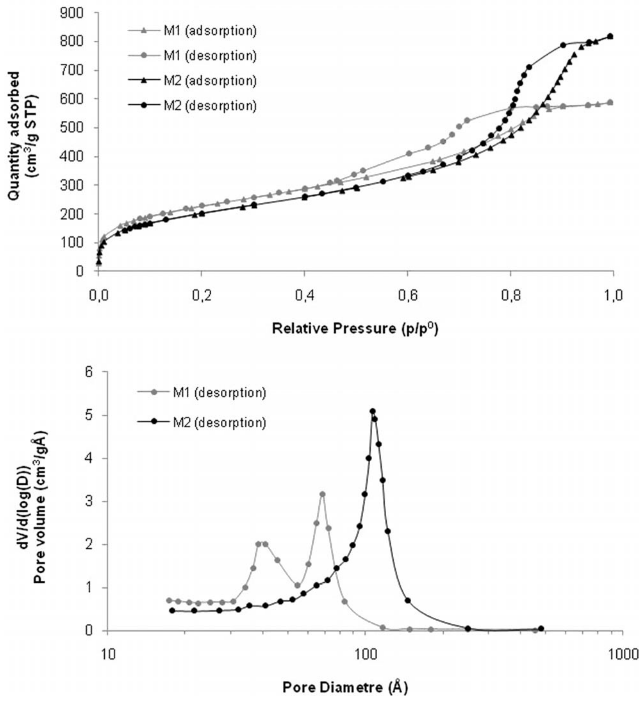
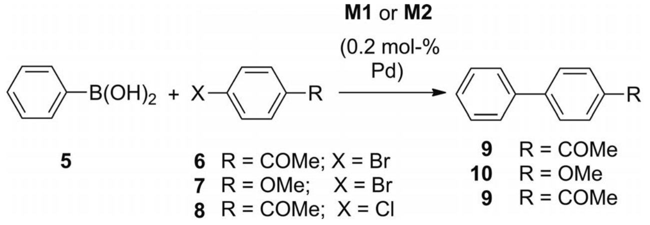


Figure 2. N_2 sorption isotherm of **M1** and **M2** and plot of the pore size distribution.

The nitrogen content of the materials was higher than expected (see the experimental section), which could be due to residual solvent (DMF) remaining in the material. Moreover, the elemental analyses revealed a Pd/Si ratio of 1:46 for **M1** and **M2**, which is only slightly different from the theoretical value of 1:41 (with complete condensation). Therefore, we can consider that most of the palladium has been incorporated within the material.

Assay of Supported Catalysts M1 and M2 in Suzuki, Heck, and Sonogashira Reactions

The supported catalysts were tested as catalytic systems (0.2 mol-% Pd) in the Suzuki cross-coupling reactions of phenylboronic acid (**5**; 1.5 equiv.) with *p*-bromoacetophenone (**6**), *p*-bromoanisole (**7**), and *p*-chloroacetophenone (**8**) to give the corresponding biaryls **9** and **10** (Scheme 2).



Scheme 2. Suzuki cross-coupling reactions catalyzed by **M1** and **M2**.

The two materials **M1** and **M2** gave efficient and fast reactions with the activated aryl bromide **6**, giving almost quantitative isolated yields of **9** in 30 min for the first cycle under the conditions indicated in Table 2 (K_2CO_3, DMF/H_2O (95:5), 110 °C). Furthermore, the catalysts could be reused for five consecutive runs, although slightly longer reaction times were required to achieve full conversions upon recycling.

Table 2. Activity and recyclability of **M1** and **M2** for the reaction of phenylboronic acid (**5**) with *p*-bromoacetophenone (**6**) to give **9** (see Scheme 2).[a]

Cycle	**M1**		**M2**	
	t [h]	**9** [%][b]	*t* [h]	**9** [%][b]
1	0.5	100	0.5	96
2	0.5	96	1	94
3	1	98	3	77
4	1.5	98	7	79
5	2	100	7	86

[a] Reactions performed in a 10 mL sealed tube under magnetic stirring using **6** (1 mmol), **M** (0.2 mol-%), **5** (1.5 equiv.), K_2CO_3 (2 equiv.), DMF/H_2O, 95:5 (2 mL), 110 °C. Full conversions at the indicated times except for third, fourth and fifth cycle for **M2**, for which about 90% conversion was observed. [b] Isolated yield.

When similar conditions were applied to the Suzuki reaction between **5** and the deactivated aryl bromide **7** (Scheme 2) good performances were obtained for the first cycle, but the activity decreased considerably in the second and third runs (conditions A, Table 3, entries 1–3). It is worth noting that the reaction progressed rapidly in the first hour and then more slowly. After some experimentation, it was found that under conditions B (KO*t*Bu, *i*PrOH, 90 °C) the reusability of the supported catalysts was noticeably improved (Table 3, entries 4–8). Full conversions were not attained under these conditions for the indicated times and the reaction was stopped when no further significant evolution was observed.

Table 3. Activity and recyclability of **M1** and **M2** for the Suzuki reaction of phenylboronic acid (**5**) with *p*-bromoanisole (**7**) to give **10** (see Scheme 2).

Entry	Conditions[a]	Cycle	M1		M2	
			t [h]	**10** [%][b]	*t* [h]	**10** [%][b]
1	A	1	21.5	82	21.5	90
2	A	2	24	93	24	84
3	A	3	24	28	24	26
4	B	1	2	74	2	75
5	B	2	5	65	5	65
6	B	3	5	68	5	72
7	B	4	5	67	5	60
8	B	5	24	65	5	67

[a] Conditions A: reactions performed in a 60 mL sealed tube under orbital stirring and an inert atmosphere, using **7** (2 mmol), **M** (0.2 mol-%), **5** (1.5 equiv.), K_2CO_3 (2 equiv.), degassed DMF/H_2O, 95:5 (4 mL), 100 °C. Conditions B: reactions performed in a 10 mL sealed tube under magnetic stirring and inert atmosphere, using **7** (2 mmol), **M** (0.2 mol-%), **5** (1.2 equiv.), KO*t*Bu (1.3 equiv.), degassed *i*PrOH (2 mL), 90 °C. [b] Isolated yield.

We then turned to the more challenging aryl chloride **8** (Scheme 2), for which a screening of different reaction conditions (base, solvent, temperature, catalyst loading, concentration) was performed using **M1** and **M2** as catalysts (Table 4). For **M1**, the best result was found using 0.2 mol-% catalyst and K_2CO_3 as base, in degassed THF/H_2O (80:20) under an inert atmosphere at 110 °C (95% GC yield after 24 h, although the reaction was almost complete after 5 h) (conditions C; Table 4, entry 4). In contrast, the use of **M2** as catalyst under the same conditions afforded only 44% GC yield of **9** after 24 h (Table 4, entry 16) whereas 88% GC yield was obtained in ethanol at 110 °C with KO*t*Bu as base (conditions D; Table 4, entry 15).

We then assessed the recyclability of **M1** and **M2** for this challenging Suzuki coupling. The best conditions (conditions C) found for **M1** (Table 4, entry 4) provided an excellent 92% isolated yield of biphenyl **9** in the first cycle, but the activity decreased drastically for the second run (< 10% yield). For **M2** under conditions D (Table 4, entry 15), a 79% isolated yield of **9** was obtained in the first cycle after 24 h and the catalyst could be recycled up to three consecutive runs (41 and 35% after 72 h). We then adopted these conditions (conditions D) for catalyst **M1** and, although the conversion and yield were lower for the first run than under conditions C, the reusability was improved (77, 53 and 29% yields after 24, 48 and 48 h, respectively, for three consecutive runs) (Table 4, entry 8).

Taking into account the isolated yields of **9** obtained under the conditions detailed in entries 8 and 15 of Table 4, the turnover numbers (TON) and turnover frequencies (TOF) for this reaction were 385 and 16 h^{-1} (for **M1**), and 395 and 16 h^{-1} (for **M2**). These values are higher than those obtained for this aryl chloride with the systems $Pd(OAc)_2$/silica-supported imidazolium salts[16] and similar to those recently found for the same reaction with other silica-supported Pd–NHC catalysts.[15,20] When the amount of catalyst was reduced from 0.2 to 0.01 mol-%, higher values were obtained but, unfortunately, the progress of the reaction was found to stop at low conversions (for **M1**: 8% at 12 h, TON 800, TOF 66 h^{-1}; for **M2**: 9% at 3 h, TON 900, TOF 300 h^{-1}).

It is worth mentioning that all the Suzuki coupling reactions with aryl bromides and chlorides gave very selective reactions because neither the homocoupling of phenylboronic acid nor formation of other side products was observed. A simple experimental protocol was followed that allowed easy recovery of the catalyst and isolation of pure

Table 4. Suzuki reaction between phenylboronic acid (**5**) and *p*-chloroacetophenone (**8**) to give **9** with supported catalysts **M1** and **M2** (see Scheme 2).

Entry	**M** [mol-%]	[**8**] (M)	Base [equiv.]	Solvent	*T* [°C]	**9** [%][a]
1	**M1** (0.2)	0.5	K_2CO_3 (2)	DMF/H_2O 95:5	110	69
2	**M1** (1.0)	0.5	K_2CO_3 (2)	DMF/H_2O 95:5	110	81
3	**M1** (0.2)	1.0	K_2CO_3 (2)	DMF/H_2O 95:5	110	63
4	**M1** (0.2)	1.0	K_2CO_3 (2)	THF/H_2O 80:20	110	95[b]
5	**M1** (0.2)	1.0	KO*t*Bu (1.3)	*i*PrOH	110	48
6	**M1** (1.0)	1.0	KO*t*Bu (1.3)	*i*PrOH	110	63
7	**M1** (0.2)	0.5	KO*t*Bu (1.3)	*i*PrOH	110	44
8	**M1** (0.2)	0.5	KO*t*Bu (1.3)	EtOH	110	86[c]
9	**M2** (0.2)	0.5	K_2CO_3 (2)	DMF/H_2O 95:5	110	66
10	**M2** (1.0)	0.5	K_2CO_3 (2)	DMF/H_2O 95:5	110	73
11	**M2** (0.2)	1.0	K_2CO_3 (2)	DMF/H_2O 95:5	110	70
12	**M2** (0.2)	0.5	K_2CO_3 (2)	DMF/H_2O 95:5	130	68
13	**M2** (0.2)	1.0	KO*t*Bu (1.3)	*i*PrOH	110	75
14	**M2** (1.0)	1.0	KO*t*Bu (1.3)	*i*PrOH	110	83
15	**M2** (0.2)	0.5	KO*t*Bu (1.3)	EtOH	110	88[d]
16	**M2** (0.2)	1.0	K_2CO_3 (2)	THF/H_2O 80:20	110	44
17	**M2** (0.2)	1.0	K_2CO_3 (2)	toluene/H_2O 80:20	130	13
18	**M2** (0.2)	0.5	KOH (2)	H_2O	110	28
19	**M2** (0.2)	0.5	Cs_2CO_3 (2)	dioxane	110	64
20	**M2** (0.2)	0.5	KOH (2)	dioxane	110	74

[a] GC yield (undecane standard) after 24 h of reaction performed in a 45 mL sealed multireactor tube under an inert atmosphere and magnetic stirring in degassed solvents. [b] 92% isolated yield, but <10% yield in the second cycle after 72 h. [c] 77% isolated yield; 53 and 29% for the second and third cycles after 48 h. [d] 79% isolated yield; 41 and 35% for the second and third cycles after 72 h.

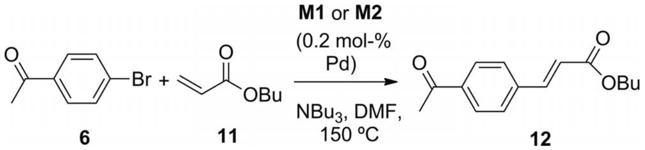
biphenyls **9** and **10** without the need for chromatographic purification (see experimental section).

In all cases, the solid catalysts turned grey after the first cycle and darkened progressively to black after several runs, which is an indication of the in situ formation of palladium nanoparticles. This was confirmed by high-resolution transmission electron microscopy (HR-TEM), which revealed particle diameters ranging from 2.3 to 4.5 nm depending on catalyst and reaction (see the Supporting Information, Table S1). Electron diffraction (ED) of the samples exhibited the characteristic pattern of face-centered cube (fcc) palladium(0) (see the Supporting Information, Figures S5, S6, and S7).

The amounts of Pd in the final biphenyl products **9** and **10** were determined by ICP-MS analysis (see the Supporting Information, Table S1), and leaching values ranging from 0.3 to 2.8% with respect to the initial palladium were found, depending on the catalyst, substrate, and conditions.

Hot filtration tests performed with all catalytic materials for the Suzuki cross-coupling reaction between phenylboronic acid (**5**) and *p*-bromoacetophenone (**6**) suggest that a homogeneous pathway plays a significant role in the Suzuki coupling reactions, with homogeneous Pd species released from the immobilized palladium systems being the true catalysts; these species would then be redeposited on the functionalized silica support.[21] When **M1** and **M2** were filtered off from the hot reaction mixture under the conditions detailed in Table 2 after 5 and 2 min, respectively (53 and 22% GC conversion of **6**) and the remaining filtrates were made to react under the same conditions after addition of a new equivalent of base, the GC conversions increased to 100 and 96%, respectively, after 30 min.

We then performed the Mizoroki–Heck reaction between *p*-bromoacetophenone (**6**) and *n*-butyl acrylate (**11**) to give *n*-butyl 4-acetyl-*trans*-cinnamate (**12**; Scheme 3). Classical conditions were adopted (NBu_3 as base in DMF at 150 °C). For **M1** and **M2**, almost quantitative isolated yields of **12** were obtained in 3 h, and the systems were successfully recycled up to five runs (Table 5). No side products were formed for any of the catalysts and the cinnamate derivative **12** was isolated in pure form without the need for chromatographic purification. Again, HR-TEM observations revealed the in situ formation of Pd^0 nanoparticles, which were larger in size than those found previously in Suzuki couplings (12.6 nm for **M1** and 19.5 nm for **M2**, see the Supporting Information, Figure S8). When the reaction progress was monitored over time in the first and second cycle for both **M1** and **M2** (see the Supporting Information, Figures S9–S10 for **M1** and Figures S11–S12 for **M2**) we found a fast reaction that required much shorter times than those mentioned in Table 5. Thus, complete conversion was attained after 15 min for the first and second runs in the case of **M1** (TON 500, TOF 2000 h^{-1}). For **M2**, it took only 10 min to reach 100% conversion in the first cycle (TON 500, TOF 3000 h^{-1}), whereas in the second cycle some decrease of activity was found (93% conversion after 20 min, TON 465, TOF 1410 h^{-1}). The reaction was also successfully performed under the same conditions with a catalyst loading of 0.01 mol-% (for **M1**: 86% conversion at 6 h, TON 8600, TOF 1433 h^{-1}; for **M2**: 85% conversion at 4.5 h, TON 8500, TOF 1900 h^{-1}). Similar values were reported by Karimi and Enders[22] in the reaction between *p*-bromoacetophenone and methyl acrylate with Pd–NHC systems immobilized in silica. For this type of supported catalyst, higher TOF could be achieved for this reaction by the use of microwave activation.[23]



Scheme 3. Mizoroki–Heck reaction catalyzed by **M1** and **M2**.

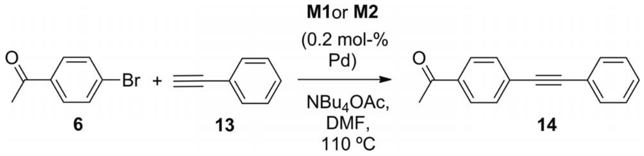
Table 5. Activity and recyclability of **M1** and **M2** for the Heck reaction between *p*-bromoacetophenone (**6**) and *n*-butyl acrylate (**11**) to give **12** (see Scheme 3).[a]

Cycle	M1 *t* [h]	 **12** [%][b]	M2 *t* [h]	 **12** [%][b]
1	3	98	3	98
2	2	99	2	99
3	3	98	3	99
4	3	96	3	98[c]
5	3	97	3	95[c]

[a] Reactions performed in a 10 mL sealed tube under magnetic stirring, with **6** (2 mmol), **11** (1.5 equiv.), NBu_3 (1.5 equiv.) in DMF (4 mL). [b] Isolated yield. [c] Yields based on ^1H NMR spectroscopic analysis. No side products observed, only starting substrate and **12**.

For both **M1** and **M2** a hot filtration test revealed the homogeneous nature of the catalytic Heck process. Thus, the catalysts were filtered off after 3 min of reaction (31 and 39% GC conversion), the filtrates were left under the same conditions and the conversions increased until 100% after 15 and 10 min, respectively. The content of Pd in the crude mixture of the Heck reaction was found to be 12.2 and 5.6 ppm for **M1** and **M2**, respectively (0.9 and 0.5% of leaching with respect to initial palladium).

Finally, the immobilized Pd–NHC complexes were assayed in the Sonogashira reaction between *p*-bromoacetophenone (**6**) and phenylacetylene (**13**), to afford 1-(4-acetylphenyl)-2-phenylacetylene (**14**), under the conditions summarized in Scheme 4 (tetrabutylammonium acetate as base, dimethylformamide, 110 °C), which had previously provided successful results for other silica-supported systems.[14b] In all cases, conversions were complete after one hour for the first run, good isolated yields of disubstituted acetylene **14** being obtained after chromatographic purification of the crude mixture (for **M1**: TON 355; for **M2**: TON 365). The materials could be recycled up to five consecutive runs, although increased reaction times were needed for complete conversion (4 h) from the second to the fifth cycles (Table 6). It is worthwhile noting that the recovered catalytic materials of the Sonogashira reactions did not contain any nanoparticles, and no darkening was observed after the successive runs.



Scheme 4. Sonogashira reaction catalyzed by **M1** and **M2**.

Table 6. Activity and recyclability of **M1** and **M2** for the Sonogashira reaction between *p*-bromoacetophenone (**6**) and phenylacetylene (**13**) to give **14** (see Scheme 4).[a]

Cycle	**M1**		**M2**	
	t [h]	**14** [%][b]	*t* [h]	**14** [%][b]
1	1	90 (71)	1	87 (73)
2	4	76	4	78
3	4	79	4	82
4	4	84	4	83
5	5	62	4	86

[a] Reactions performed in a 10 mL sealed tube under magnetic stirring, with **6** (2 mmol), **13** (1.5 equiv.), NBu_4OAc (1.45 equiv.) in DMF (4 mL). [b] GC yield (undecane standard). Isolated yield after chromatography given in brackets.

The content of Pd in the crude mixture of the Sonogashira reaction was determined by ICP-MS and revealed that leaching was very low (3.9 and 3.1 ppm for **M1** and **M2**, respectively, corresponding to a loss of 0.3 and 0.2% with respect to initial palladium).

Monitoring the progress of the reaction over time showed that the Sonogashira reaction was faster than expected. For the first run with catalyst **M1** complete conversion was achieved after 5 min. The catalyst had lost some activity in the second cycle, with conversion reaching a value of 90% after 10 min, and the reaction subsequently progressed very slowly (see the Supporting Information, Figures S13–S14).

The reaction was even faster with **M2** than with **M1** (100% GC conversion after 2 min for the first run; for the second run the activity decreased and required 10 min for the reaction to complete) (see the Supporting Information, Figure S15).

Due to the fast processes observed, we then performed the reaction with a much lower loading of catalyst (0.01 mol-%). Under these conditions, the GC yields of alkyne **14** after 1.5 h were 54% for **M1** (TON 5400, TOF 3600 h^{-1}) and 48% for **M2** (TON 4800, TOF 3200 h^{-1}). It is worthwhile mentioning that silica-supported Pd–NHC systems have rarely been used as recyclable catalysts in the Sonogashira reaction.[15] To the best of our knowledge, only one report describes the coupling between iodobenzene and phenylacetylene and, in this case, quite low yields and TOF values (0.08 h^{-1}) were reported.[24] A hot filtration test for the second run with **M1** and **M2** also suggested a homogeneous pathway, despite the fact that, in these cases, no nanoparticles were formed.

The reaction cycle for C–C coupling reactions with supported Pd catalysts may be complex and involve a considerable number of processes with Pd colloids on the support or in the solution, molecular Pd^0, and/or Pd^{II} species either supported or released in the solution, with the nature of the truly active catalytic species not being well-established in most cases.[25] The dissolution and redeposition of palladium has been proven by several authors.[21,25a] In our case, hot filtration tests suggest that the reactions take place, at least in part, through a homogeneous pathway. Whereas in the Suzuki and Heck reactions the formation of Pd nanoparticles is observed upon recycling the materials, this is not the case for the Sonogashira reaction. Both the inorganic matrix and the NHC moieties of our hybrid silica materials should have a contribution to the stabilization of nanoparticles or other Pd species formed in the processes. However, palladium nanoparticles have also been claimed to act as a reservoir in C–C coupling reactions, from which a small amount of leached palladium atoms or low molecular weight catalytically active Pd species may be formed.[25]

Conclusions

Two hybrid silica gels (**M1** and **M2**) have been prepared by cocondensation of TEOS with silylated Pd–NHC complexes (**3** and **4**). These were obtained by reaction of a silylated mesityl-imidazolium derivative (**2**) with $Pd(acac)_2$ or $PdCl_2$/3-chloropyridine, respectively. These two supported catalysts were evaluated for the Heck, Suzuki, and Sonogashira coupling reactions. It is worth mentioning that, although the corresponding homogeneous complexes [Pd(acac)Cl(NHC)] and [$PdCl_2$(3-ClPyr)(NHC)] have not been described in Heck and Sonogashira reactions, both materials performed efficiently in all three catalytic reactions and, notably, very fast reactions and excellent recyclabilities (for at least five runs) were obtained for aryl bromides. For the Suzuki reaction with the challenging aryl chloride **8**, significantly better conversions were achieved than with previously reported[16] systems with imidazolium-immobilized silicas, and the catalysts could be reused for up to three runs. Moreover, no homocoupling reaction was observed and no other side products were obtained in the Suzuki or Heck processes. Hence, the corresponding coupling products were easily obtained without any need for chromatographic separation. For the copper- and phosphane-free Sonogashira reaction, we found TON and TOF values up to 5400 and 3600 h^{-1}, respectively, which are much higher than those reported for other silica-supported Pd–NHC systems previously described. Moreover, we have shown here that the materials act as a reservoir of the Pd species that actually react in solution. In the Suzuki and Heck reactions the formation of Pd nanoparticles is observed upon recycling the materials, whereas this is not the case for the Sonogashira reaction. However, palladium nanoparticles have also been claimed to be a reservoir in C–C coupling reactions, from which a small amount of leached palladium atoms or low molecular weight catalytically active Pd species may be formed. Furthermore, this work demonstrates that the use of periodic mesoporous materials obtained with surfactants is not a prerequisite and that a simple sol-gel cocondensation with TEOS to generate nonuniform mesoporosity is enough to achieve such performance. Similar efficiency (recyclability, selectivity, yield, and cleanliness of the reaction) was quite recently observed for the direct asymmetric aldol reaction with supported hybrid silica-based organocatalysts derived from prolinamide, despite the low surface area obtained through the sol-gel process.[26]

Experimental Section

General Remarks: When required, experiments were carried out with standard high vacuum and Schlenk techniques, and the solvents were dried and distilled just before use following standard procedures. Solution ^{1}H and ^{13}C NMR spectra were recorded with Bruker DRX-250 MHz, DPX-360 MHz, AVANCE-III 400 MHz or AVANCE 500 MHz spectrometers. The ^{29}Si CP-MAS solid-state NMR spectra were recorded with a Bruker AV-400-WB spectrometer. All NMR experiments were performed at the Servei de Ressonància Magnètica Nuclear of the Universitat Autònoma de Barcelona. HRMS were recorded by the Servei d'Anàlisi Química at the Universitat Autònoma de Barcelona, with an ESI hybrid quadrupole time of flight microTOFQ spectrometer from Bruker Daltonics. IR data were obtained with a Bruker Tensor 27 spectrophotometer with ATR Golden Gate and with a Perkin–Elmer (System 2000 FTIR) spectrophotometer. N_2-sorption isotherms were obtained with a Micromeritics ASAP2020 analyzer at the Institut Charles Gerhardt Montpellier after degassing the materials at 55 °C for 30 h under vacuum. The surface areas and the pore-size distributions were determined by using the Brunauer–Emmett–Teller (BET) and the Barrett–Joyner–Halenda (BJH) methods, respectively. Elemental analyses were performed at the Serveis Cientificotècnics of the Universitat de Barcelona, at the Servei d'Anàlisi of the Universitat Autònoma de Barcelona or at the Servei de Microanàlisi of the CSIC in Barcelona. The content of palladium was determined at the Serveis Cientificotècnics of the Universitat de Barcelona by inductively coupled plasma (ICP) analysis. High-resolution transmission electron microscopy (HR-TEM) observations were carried out at the Servei de Microscòpia of the Universitat Autònoma de Barcelona with a JEOL JEM 2011 (200 kV). Chromatographic purifications were performed under N_2 pressure using 230–400 mesh silica gel (flash chromatography). Distilled and deionized water (MilliQ) was used for the sol-gel process. GC analyses were performed with an Agilent Technologies 7890A instrument equipped with an Agilent HP-5 capillary column. 1-Mesitylimidazole (**1**),[17b] was prepared according to previously described procedures. Compounds **9**,[27] **12**,[28] and **14**[29] are described in the literature and their spectroscopic data matched those previously reported.

1-Mesityl-3-[3-(triethoxysilyl)propyl]-1*H*-imidazol-3-ium Chloride (2): A mixture of 1-mesitylimidazole **1** (0.601 g, 3.23 mmol) and (3-chloropropyl)triethoxysilane (0.90 g, 3.55 mmol) was stirred under argon at 90 °C for 5 days. The volatiles were removed under vacuum and the residue was thoroughly washed with anhydrous pentane to afford **2** as a solid (1.166 g, 85%). M.p. 134–135 °C (Lit.[18] m.p. 135 °C). ^{1}H NMR (360 MHz, $CDCl_3$): δ = 10.54 (s, 1 H, NC*H*N), 7.75 (s, 1 H, NC*H*=CHN), 7.20 (s, 1 H, NCH=C*H*N), 6.91 (s, 2 H, Ar–H), 4.64 (t, ^3J = 6.5 Hz, 2 H, NC*H*$_2$), 3.74 (q, ^3J = 7.0 Hz, 6 H, OC*H*$_2$CH$_3$), 2.26 (s, 3 H, Ar-CH$_3$), 1.99 (m, 8 H, Ar-CH$_3$ and NCH$_2$C*H*$_2$), 1.14 (t, ^3J = 7.0 Hz, 9 H, OCH$_2$C*H*$_3$), 0.55–0.60 (m, 2 H, SiC*H*$_2$) ppm. ^{13}C NMR (90 MHz, $CDCl_3$): δ = 141.1, 138.6, 134.1, 130.8, 129.8, 123.2, 122.8, 58.6, 52.0, 24.6, 21.1, 18.3, 17.6, 6.9 ppm.

Synthesis of the Monosilylated Pd–NHC Complex 3: In a Schlenk tube under argon, **2** (0.533 g, 1.25 mmol) was suspended in anhydrous dioxane (18 mL). This suspension was transferred to a Schlenk tube containing Pd(acac)$_2$ (0.318 g, 1.04 mmol) and the resulting mixture was stirred for 20 h at 100 °C under argon. The solvent was removed under vacuum, the residue was extracted with anhydrous Et_2O and the resulting suspension filtered off. The filtrates were concentrated under vacuum and the final solid was further washed with anhydrous pentane to afford **3** as a yellow solid (0.547 g, 83%). M.p. 132–134 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.13 (d, ^3J = 1.5 Hz, 1 H, C*H*=CH), 7.01 (s, 1 H, Ar–H), 6.89 (s, 1 H, Ar–H), 6.84 (d, ^3J = 1.5 Hz, 1 H, CH=C*H*), 5.17 (s, 1 H, CH acac), 5.07–5.01 (m, 1 H, C*H*HCH$_2$CH$_2$Si), 4.45–4.39 (m, 1 H, CH*H*CH$_2$CH$_2$Si), 3.82 (q, ^3J = 7.0 Hz, 6 H, OC*H*$_2$CH$_3$), 2.34 (s, 3 H, Ar-CH$_3$), 2.24 (s, 3 H, Ar-CH$_3$), 2.15 (m, 2 H, C*H*$_2$CH$_2$Si), 2.01 (s, 3 H, Ar-CH$_3$), 1.91 (s, 3 H, CH$_3$ acac), 1.75 (s, 3 H, CH$_3$ acac), 1.22 (t, ^3J = 7.0 Hz, 9 H, OCH$_2$C*H*$_3$), 0.80–0.72 (m, 2 H, C*H*$_2$Si) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 187.4 (C=O), 183.5 (C=O), 151.9 (Pd-C), 139.2 (C), 136.7 (C), 135.9 (C), 135.0 (C), 129.7 (CH), 128.6 (CH), 123.4 (CH), 121.9 (CH), 99.8 (CH), 58.6 (CH$_2$), 53.5 (CH$_2$), 27.3 (CH$_3$), 25.7 (CH$_3$), 24.9 (CH$_2$), 21.3 (CH$_3$), 18.8 (CH$_3$), 18.4 (CH$_3$), 17.9 (CH$_3$), 7.5 (CH$_2$-Si) ppm. IR (ATR): $\tilde{\nu}$ = 2971, 2920 and 2885 (H–Csp^3), 1579 and 1514 (C=O–Pd), 1101 and 1075 (Si–O–C) cm^{-1}. IR (PEG): $\tilde{\nu}$ = 339, 301 and 215 (Pd–Cl) cm^{-1}. HRMS (ESI): calcd. for $C_{26}H_{41}ClN_2O_5PdSi$ + Na$^+$ [M + Na$^+$] 655.1403; found 655.1396.

Synthesis of the Monosilylated Pd–NHC Complex 4: In a Schlenk tube under argon, $PdCl_2$ (0.266 g, 1.50 mmol), **2** (0.713 g, 1.67 mmol), and K_2CO_3 (99%; 1.038 g, 7.41 mmol) were suspended in freshly distilled 3-chloropyridine (6.00 mL, 1.21 g/cm^3, 64 mmol). The mixture was stirred overnight at 80 °C under argon, then anhydrous CH_2Cl_2 (6 mL) was added and the solution was placed on a short silica gel/Celite® column and eluted with anhydrous CH_2Cl_2 (3 × 4.5 mL). The volatiles of the eluted fraction were distilled off under vacuum (1 Torr, 40 °C) and the residue was washed with anhydrous pentane, affording **4** (0.734 g, 72%) as a pale-brown solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.85 (d, ^4J = 2.5 Hz, 1 H, Ar–H pyr), 8.75 (dd, ^3J = 5.5 Hz, ^5J = 1.0 Hz, 1 H, Ar–H pyr), 7.68–7.66 (m, 1 H, Ar–H pyr), 7.21–7.15 (m, 1 H, Ar–H pyr), 7.00–6.90 (m, 4 H, Ar–H Mes and NC*H*=C*H*N), 4.74 (t, ^3J = 7.5 Hz, 2 H, C*H*$_2$CH$_2$CH$_2$Si), 3.86 (q, ^3J = 7.0 Hz, 6 H, OC*H*$_2$CH$_3$), 2.35 (s, 3 H, Ar-CH$_3$), 2.25 (s, 6 H, Ar-CH$_3$), 1.25–1.22 (m, 2 H, C*H*$_2$CH$_2$Si), 1.25 (t, ^3J = 7.0 Hz, 9 H, OCH$_2$C*H*$_3$), 0.83–0.81 (m, 2 H, C*H*$_2$Si) ppm. Signals corresponding to free 3-chloropyridine were also observed due to a complexation–decomplexation equilibrium. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 150.5, 149.5, 149.1, 147.7, 139.3, 137.9, 136.6, 136.5, 135.9, 135.1, 135.0, 132.4, 132.3, 129.35, 129.27, 129.2, 128.3, 124.6, 124.5, 124.1, 122.2, 121.8, 58.7 (CH$_2$), 53.6 (CH$_2$), 24.2 (CH$_2$), 21.2 (CH$_3$), 19.0 (2 × CH$_3$), 18.5 (CH$_3$), 7.6 (CH$_2$-Si) ppm. IR (ATR): $\tilde{\nu}$ = 3092 (H–Csp^2), 2971 and 2918 (H–Csp^3), 1463, 1419, 1220, 1073, 825, 691 cm^{-1}. IR (PEG): $\tilde{\nu}$ = 379, 348 and 323 (Pd–Cl) cm^{-1}. MS (ESI): *m*/*z* (%) = 644.2 (100) [*M* – Cl]$^+$. $C_{26}H_{38}Cl_3N_3O_3PdSi$ (681.45): calcd. C 45.82, H 5.62, N 6.17, Cl 15.61; found C 45.52, H 5.06, N 6.91, Cl 16.03.

Synthesis of M1: Complex **3** (0.378 g, 0.598 mmol) and TEOS (98%; 5.06 g, 23.8 mmol) were dissolved in anhydrous DMF (14.7 mL). To this solution was added a mixture of distilled and deionized water (1.49 mL, 82.5 mmol) and NH_4F (1 M aqueous solution, 0.260 mL, 14.4 mmol H_2O, 0.260 mmol F) in anhydrous DMF (9.8 mL). The resulting yellow solution (molar composition **3**/TEOS/H_2O/F = 1:40:162:0.4) was shaken for 1 min at room temperature and then allowed to stand. After 1 h a gel formed that was aged for 5 days at room temperature. The gel was crushed, filtered, and washed with water (× 2), EtOH (× 3), and CH_2Cl_2 (× 3). The resulting solid was dried overnight at 60 °C under vacuum (1 Torr) affording **M1** (1.81 g, 0.260 mmol Pd/g) as a pale-yellow solid. ^{29}Si CP-MAS NMR (79.5 MHz): δ = –58.6 (T^2), –67.6 (T^3), –92.8 (Q^2), –102.0 (Q^3), –110.9 (Q^4) ppm. $C_{20}H_{26}ClN_2O_2$-$SiO_{1.5}Pd{\cdot}40SiO_2$ (2923.8) calcd. (considering complete condensation) C 8.22, H 0.89, N 0.96, Cl 1.21, Si 39.4, Pd 3.64; found C 11.44, H 2.26, N 1.88, Cl 1.09, Si 33.9, Pd 2.77. S_{BET} 810 m^2/g; pore diameter: bimodal distribution centered at 42 and 70 Å; pore volume: 0.91 cm^3/g.

Synthesis of M2: Complex **4** (0.738 g, 1.08 mmol) and TEOS 98% (9.203 g, 43.3 mmol) were dissolved in anhydrous DMF (26.6 mL). To this solution was added a mixture of distilled and deionized water (2.74 mL, 152 mmol) and NH_4F (1 M aqueous solution, 0.445 mL, 24.7 mmol H_2O, 0.445 mmol F) in anhydrous DMF (17.7 mL). The resulting yellow solution (molar composition **4**/TEOS/H_2O/F = 1:40:163:0.4) was shaken for one minute at room temperature and then allowed to stand. After 3 h a gel formed that was aged for 5 days at room temperature. At this time, the gel was crushed, filtered, and washed with water (× 2), EtOH (× 3), and CH_2Cl_2 (× 3). The resulting solid was dried overnight at 60 °C under vacuum (1 Torr) affording **M2** (3.65 g, 0.233 mmol Pd/g) as a pale-yellow solid. ^{29}Si CP-MAS NMR (79.5 MHz): δ = –59.1 (T^2), –67.0 (T^3), –92.0 (Q^2), –101.8 (Q^3), –111.5 (Q^4) ppm. $C_{20}H_{23}Cl_3N_3O_3PdSiO_{1.5}{\cdot}40SiO_2$ (3021.7) calcd. (considering complete condensation) C 7.95, H 0.76, N 1.39, Si 38.11, Pd 3.52; found C 11.65, H 2.29, N 1.97, Si 30.61, Pd 2.48. S_{BET} 730 m^2/g; pore diameter: distribution centered at 110 Å; pore volume: 1.26 cm^3/g.

Catalytic Tests

Procedure for the Suzuki Cross-Coupling between 5 and 6 To Give 9 (Table 2): In a sealed tube (10 mL) with a magnetic stir bar, the supported catalyst (0.002 mmol), *p*-bromoacetophenone (**6**; 0.203 g, 1.00 mmol), phenylboronic acid (**5**; 0.187 g, 1.5 mmol), and K_2CO_3 (0.279 g, 2.0 mmol) were suspended in a mixture of DMF and H_2O (95:5, 2 mL). The mixture was stirred at 110 °C and the reaction was monitored by GC analysis. After the time indicated in Table 2, EtOAc (5 mL) was added, the suspension was centrifuged, and the supernatant solution separated; this process was repeated twice. The ethyl acetate from the combined layers was removed under reduced pressure and, upon addition of water to the remaining liquid phase, a crude product precipitated that was filtered off and washed with water. The latter was dissolved in EtOAc, the solution was dried with anhydrous Na_2SO_4, and the solvent was removed under reduced pressure to give **9** as a white solid. The catalyst that had been separated by centrifugation was washed successively with EtOH (× 2), water (× 2), EtOH (× 2), and Et_2O (× 2), then dried under vacuum (2 Torr) and directly reused in the next cycle.

Procedure for the Suzuki Cross-Coupling between 5 and 7 To Give 10 (Conditions A, Table 3): In a sealed multireactor tube (60 mL) with orbital stirring under argon, the supported catalyst (0.004 mmol), *p*-bromoanisole (**7**; 0.255 mL, 1.49 g/cm^3, 2.0 mmol), phenylboronic acid (**5**; 0.373 g, 3.0 mmol), and K_2CO_3 (0.563 g, 4.0 mmol) were suspended in a degassed mixture of DMF/H_2O (95:5, 4 mL). The mixture was stirred at 100 °C and the reaction was monitored by GC analysis. After the time indicated in Table 3, EtOAc (10 mL) was added to the reaction mixture, the suspension was centrifuged and the supernatant solution was separated; this process was repeated twice. The ethyl acetate from the combined layers was removed under reduced pressure and, upon addition of water to the remaining liquid phase, compound **10** precipitated, which was filtered off and washed with water. Compound **10** was dissolved again in EtOAc, the solution was dried with anhydrous Na_2SO_4, and the solvent was removed under reduced pressure to give **10** as a white solid. The catalyst that had been separated by centrifugation was washed successively with EtOH (× 2), water (× 2), EtOH (× 2), and Et_2O (× 2), then dried under vacuum (2 Torr) and directly reused in the next cycle.

Procedure for the Suzuki Cross-Coupling between 5 and 7 To Give 10 (Conditions B, Table 3): In a sealed tube (10 mL) with a magnetic stir bar under argon, the supported catalyst (0.004 mmol), *p*-bromoanisole (**7**; 0.255 mL, 1.49 g/cm^3, 2.0 mmol), phenylboronic acid (**5**; 0.301 g, 2.4 mmol) and KO*t*Bu (0.300 g, 2.6 mmol) were suspended in degassed 2-propanol (2 mL). The mixture was stirred at 90 °C and the reaction was monitored by GC analysis. After the time indicated in Table 3, EtOAc (5 mL) was added to the reaction mixture, the suspension was centrifuged, and the supernatant solution separated; this process was repeated twice. The ethyl acetate from the combined layers was removed under reduced pressure and, upon addition of water to the remaining liquid phase, compound **10** precipitated, which was filtered off and washed with water. Compound **10** was dissolved again in EtOAc, the solution was dried with anhydrous Na_2SO_4, and the solvent was removed under reduced pressure to furnish **10** as a white solid. The catalyst that had been separated by centrifugation was washed successively with EtOH (× 2), water (× 2), EtOH (× 2) and Et_2O (× 2), then dried under vacuum (2 Torr) and directly reused in the next cycle.

Procedure for the Suzuki Cross-Coupling between 5 and 8 To Give 9 by Using K_2CO_3 as Base and THF/H_2O (80:20) as Solvent (Entries 4 and 16, Table 4): In a sealed multireactor tube (45 mL) with a magnetic stir bar under argon, the supported catalyst (0.004 mmol), *p*-chloroacetophenone (**8**; 2.0 mmol), phenylboronic acid (**5**; 3.0 mmol), and K_2CO_3 (4.0 mmol) were suspended in a degassed mixture of THF/H_2O (80:20, 2 mL). The mixture was stirred at 110 °C and the reaction was monitored by GC analysis. After the time indicated in Table 4, EtOAc (10 mL) was added to the reaction mixture, the suspension was centrifuged, and the supernatant solution was separated; this process was repeated twice. The ethyl acetate from the combined layers was removed under reduced pressure and, upon addition of water to the remaining liquid phase, a crude product precipitated that was filtered off and washed with water. The latter was dissolved in EtOAc, the solution was dried with anhydrous Na_2SO_4, and the solvent was removed under reduced pressure to give **9** as a white solid. The supported catalyst that had been separated by centrifugation was washed successively with EtOH (× 2), water (× 2), EtOH (× 2), and Et_2O (× 2), then dried under vacuum (2 Torr) and directly reused in the next cycle.

Procedure for the Suzuki Cross-Coupling between 5 and 8 To Give 9 by Using KO*t*Bu as Base and EtOH as Solvent (Table 4, entry 15): In a sealed multireactor tube (45 mL) with a magnetic stir bar under argon, the supported catalyst (0.004 mmol), *p*-chloroacetophenone (**8**; 2.0 mmol), phenylboronic acid (**5**; 3.0 mmol), and KO*t*Bu (2.7 mmol) were suspended in degassed EtOH (4 mL). The mixture was stirred at 110 °C and the reaction was monitored by GC analysis. After the time indicated in Table 4, EtOAc (10 mL) was added to the reaction mixture, the suspension was centrifuged, and the supernatant solution was separated; this process was repeated twice. The ethyl acetate from the combined layers was removed under reduced pressure and, upon addition of water to the remaining liquid phase, a crude product precipitated that was filtered off and washed with water. The latter was dissolved back in EtOAc, the solution was dried with anhydrous Na_2SO_4, and the solvent was removed under reduced pressure to give **9** as a white solid. The supported catalyst that had been separated by centrifugation was washed successively with EtOH (×2), water (×2), EtOH (×2), and Et_2O (×2), then dried under vacuum (2 Torr) and directly reused in the next cycle.

Procedure for the Heck Reaction between 6 and 11 To Give 12 (Table 5): In a sealed tube (10 mL) with a magnetic stir bar, the supported catalyst (0.004 mmol), *p*-bromoacetophenone (**6**; 2.0 mmol), and *n*-butyl acrylate (**11**; 3.0 mmol) were suspended in DMF (4 mL) and the mixture was heated at 150 °C. Tributylamine (3.0 mmol) was added and the reaction mixture was maintained at 150 °C while stirring (progress of the reaction monitored by GC analysis). After the time indicated in Table 5, DMF (3 mL) was added to the reaction mixture, the suspension was centrifuged, and the supernatant solution was separated; this process was repeated once more and the solvent from the combined layers was removed under vacuum. Water was added to the residue and compound **12** was extracted with EtOAc. The combined organic layers were dried with anhydrous Na_2SO_4 and concentrated under reduced pressure to give **12** as an oily product. The supported catalyst that had been separated by centrifugation was washed successively with water, EtOH, and Et_2O, then dried under vacuum (2 Torr) and directly reused in the next cycle.

Procedure for the Sonogashira Reaction between 6 and 13 To Give 14 (Table 6): In a sealed tube (10 mL) with a magnetic stir bar, the supported catalyst (0.004 mmol), *p*-bromoacetophenone (**6**; 2.0 mmol) and Bu_4NOAc (2.85 mmol) were suspended in DMF (4 mL) and the mixture was heated at 110 °C. Phenylacetylene **13** (3.0 mmol) was added and the reaction mixture was maintained at 110 °C while stirring (progress of the reaction monitored by GC analysis). After the time indicated in Table 6, DMF (3 mL) was added to the reaction mixture, the suspension was centrifuged, and the supernatant solution was separated; this process was repeated once more and the solvent from the combined layers was removed under vacuum. Water was added to the residue and compound **14** was extracted with EtOAc. The combined organic layers were dried with anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was purified by flash chromatography on silica gel (hexane/EtOAc, 20:1) to afford **14** as a pale-brown solid. The supported catalyst that had been separated by centrifugation was washed successively with water, EtOH, and Et_2O, then dried under vacuum (2 Torr) and directly reused in the next cycle.

Supporting Information (see footnote on the first page of this article): Figures S1–S15 and Table S1, as well as the characterization data for **2**, **3**, **4**, **M1**, and **M2** (^{29}Si CP-MAS NMR, IR, N_2-sorption measurements).

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