Hydrogenolysis of C−O Chemical Bonds of Broad Scope Mediated by a New Spherical Sol–Gel Catalyst

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This study is dedicated to Professor Franck Dumeignil, Lille University and CNRS (France), for all he has done to advance the second generation biorefinery from a conceptual to a practical reality

The new spherical sol–gel hybrid material Silia*Cat* Pd[0] selectively mediates the hydrogenolysis of aromatic alcohols, aldehydes, and ketones by using an ultralow catalytic amount (0.1 mol % Pd) under mild reaction conditions. The broad reaction scope as well as the catalyst's superior activity and pronounced stability open the route to green and convenient reductive deoxygenation processes of primary synthetic relevance in chemical research as well as in the fine chemical and petrochemical industries.

1. Introduction

The hydrogenolysis of C−O and C=O chemical bonds in alcohol, ester, and carbonyl compounds over supported metal nanoparticles (NPs) with H_2 is an important reaction used in synthetic organic chemistry and in manufacturing active pharmaceutical ingredients,[1] as well as in biomass conversion in the emerging biorefinery to cleave C−OH bonds with hydrogen to access valuable platform chemicals.[2] Numerous solid catalysts are available to selectively mediate the scission of C−O bonds with H_2 including supported Ni,[3] PtO[4] (Adams catalyst), Rh and Ir,[5] Cu[6] (copper chromite), and Pd catalysts.[7] The reaction is usually carried out under hydrogen pressure at relatively high temperature (usually above 150 °C and often above 200 °C), promoting NP aggregation. Hence, intense research efforts are being devoted to finding catalysts of stable performance, for example, through encapsulation of Cu,[8] Ni,[9–11] and Pd[12] NPs in the inner porosity of porous oxides. However, as put by Samec and co-workers in 2013, when reporting on the Pd/C-catalyzed transfer hydrogenolysis of primary, secondary, and tertiary benzylic alcohols by formic acid,[13] the hydrogenolysis of benzylic alcohols has been studied to a lesser extent, with the noticeable exception of Yang and co-workers[14] who reported a clean and simple method (and proposed a reaction mechanism based on Pd[0] formation) for the reductive deoxygenation of aromatic ketones and benzylic alcohols using palladium chloride ($PdCl_2$) as the catalyst, and polymethylhydrosiloxane as the hydride source. Starting from conventional palladium on activated charcoal (Pd/C), numerous solid palladium catalysts are available to selectively mediate hydrogenolysis reactions under mild or very mild conditions. However, even though there is broader utilization of said catalysts using valued palladium, it requires that high product yields are achieved by using low catalyst amounts while minimizing leaching[1] of the valued palladium. This is particularly important in light of forthcoming wide utilization of reactions under flow conditions for active pharmaceutical ingredient (API) manufacturing, in which long-term stability of the catalyst is an essential requirement.[15]

Silia*Cat* Pd[0], namely a hybrid organically modified silica (ORMOSIL) glass encapsulating palladium NPs, which combines high porosity with organic functionality,[16,17] is a hydrogenation catalyst that selectively mediates a number of important reactions including the highly selective debenzylation of aryl benzyl ethers, benzyl esters, and benzyl amines,[18] and the hydrogenation of functionalized nitroarenes,[19] olefins,[20] vegetable oils,[21] and squalene.[22] More recently, we reported that the

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[1] Leaching values are given in $mg\,kg^{-1}$ of API. Limit of detection: $LOD_{Pd,Si} = 0.05$ ppm in solution (100 $mg\,mL^{-1}$ concentration) or 0.50 $mg\,kg^{-1}$ in the crude product.

solvent-free hydrogenation of the latter oil requires a catalyst with nanostructured spherical morphology.[23] In this work, we report that the glassy hybrid spherical Silia*Cat* Pd[0] material is a highly selective mediator for the hydrogenolysis of aromatic alcohols, aldehydes, and ketones under very mild conditions, with ultralow amounts of Pd leaching in the final product. We compared the performance of this new catalyst with that of several commercial catalysts including Pd/polyethylenimine/SiO₂, Pd/SiO₂, and Pd/C. Silia*Cat* Pd[0] is a recyclable catalyst and retains its ideal spherical morphology, thereby providing research laboratories and industry with a suitable economic method to make substances in high demand at low cost by using an entirely green process.

Experimental Section

Materials

All reactions were performed on a multigram scale, using anhydrous ethanol or solvents of HPLC grade. Unless otherwise noted, reagents were commercially available and used without purification. The commercial palladium catalyst 5% Pd/C (from Sigma Aldrich), ROYER catalyst (3 wt% Pd[0]/polyethylenimine/SiO₂, from Strem Chemicals) and Pd Escat 1351 (5 wt% Pd[0]/SiO₂, from Strem Chemicals) were used as received from the suppliers.

Sample Characterization

Physical properties of the Silia*Cat* Pd[0] catalyst were determined by using X-ray diffraction (XRD), transmission electron microscopy (TEM), N₂ isotherms, ^{29}Si MAS NMR spectroscopy, and inductively coupled plasma–optical emission spectroscopy (ICP-OES). The XRD analyses were performed on a Siemens D-5000 X-ray diffractometer equipped with a monochromatic CuKα radiation source ($\lambda = 1.5418$). The spectra were recorded in the $2\theta = 0$–30° range for the undoped ORMOSIL support and $2\theta = 10$–90° for the Silia*Cat* Pd[0] catalyst, in both cases at a scan speed of $1°\,m^-$ and a step scan of 0.02°. The Powder Diffraction File of The International Centre for Diffraction Data was used to identify the diffraction peaks characteristic of crystalline Pd[0] with a face centered cubic (fcc) lattice. A tube voltage of 40 kV and a current of 100 mA were used for scanning. The TEM images were taken by using a JEOL-2010 microscope equipped with a LaB6 electron gun source operated at 200 kV. Nitrogen adsorption and desorption isotherms were measured at 77 K by using a Micrometrics TriStar II 3020 system. The resulting data were analyzed with the TriStar II 3020 version 3.02 software. Barrett–Joyner–Halenda (BJH) desorption branches were used to calculate the pore-size distribution. Solid-state ^{29}Si NMR spectra were recorded on a Bruker Avance spectrometer (Milton, ON, Canada) at a silicon frequency of 79.5 MHz. The sample was spun at 8 kHz at magic angle at room temperature in a 4 mm ZrO rotor. A Hahn echo sequence synchronized with the spinning speed was used while applying a TPPM15 composite pulse decoupling during acquisition. A total of 2400 acquisitions were recorded with a recycling delay of 30 s. The leaching of Pd and Si was assessed by ICP-OES analysis of the crude product in DMF (concentration 100 mg mL^{-1}), using a PerkinElmer Optima 2100 DV system. Values measured are reported as milligrams of Pd and as milligrams of Si per kilogram of crude product.

General Procedure for the Catalytic Hydrogenolysis of Aromatic Alcohols, Aldehyde and Ketones over Silia*Cat* Pd[0]

Multigram hydrogenolysis reactions of aromatic alcohols, aldehyde, and ketones were carried out in an Ace Glass 6437 system equipped with a batch glass reactor, under a maximum pressure of 3 bar H₂ at 70–100°C. The 500 mL glass reactor was charged with 250 mL reagent solution (375 mmol reagent) and 1.56 g Silia*Cat* Pd[0] for 0.1 mol% Pd. Mechanical stirring was then set at 800 rpm and the reaction mixture degassed five times, replacing three times the vacuum by Ar, and twice Ar by H₂, after which the desired hydrogen pressure was set and kept at 3 bar. The reaction temperature was then raised from 22°C to the desired reaction temperature and kept at this temperature for several hours until maximum conversion, after which the reaction mixture was cooled to 20°C. The solid catalyst recovered by filtration was washed, dried, and stored prior to reuse. The isolated yield was assessed by simple isolation of product by rotary evaporator distillation at 20°C. Thus-obtained products are generally very pure and no further chromatographic purification required.
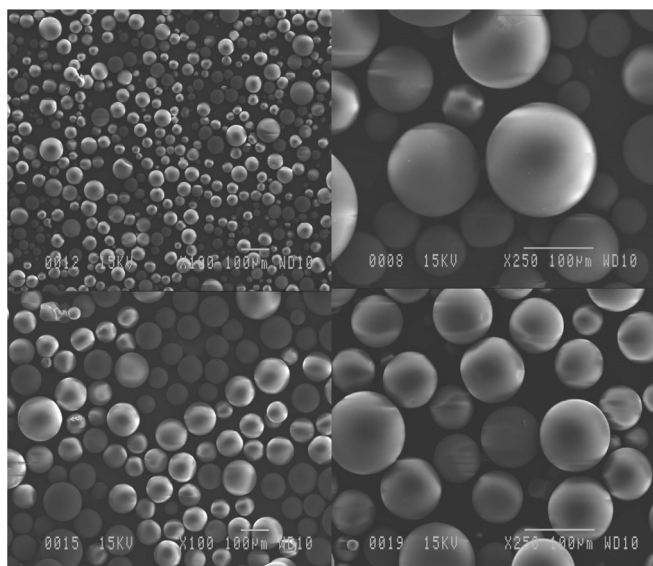
GC-MS analyses were performed by using a 7890B GC System (Agilent Technologies) equipped with a HP-5MS 30 m capillary column [(5%-phenyl)-methylpolysiloxane, 0.25 mm inner diameter and 0.25 μm film thickness] and with a mass spectrometer 5977B mass-selective detector operated in electron impact ionization mode (70 eV). GC-MS analyses were carried out in split mode, using helium as the carrier gas (1 mL min^{-1} flow rate). The injection temperature was 250°C, the interface was set at 325°C, and the ion source was adjusted to 230°C. The column was maintained at an initial temperature of 50°C for 4.5 min, and then ramped to 325°C at 100°C min^{-1}, where it was maintained for 5 min. Mass spectra were recorded at 5.5 scans s$^-$ (m/z 50–550). The identification of the compounds was based on comparison of their retention times with those of authentic samples, and on comparison of their EI-mass spectra with the NIST/NBS, Wiley library spectra, and the literature.

2. Results and Discussion

Silia*Cat* Pd[0] is a heterogeneous catalyst obtained through the alcohol-free sol–gel polycondensation of alkoxysilanes such as methyltrimethoxysilane (MTES).[24] The catalyst, now available in spherical morphology (Figure 1), is comprised of catalytically active Pd NPs encapsulated within the spherical mesoporous ORMOSIL matrix.

The presence of highly dispersed palladium NPs (ca. 2–4 nm) entrapped within the inner porosity of the lipophilic organosilica matrix[25] was clearly revealed by TEM analysis before and after scale-up catalyst synthesis (Table 1, Figures 2 a and 2 b). The crystalline nature of the active nanophase is evident from the XRD pattern of the catalyst powder (Figure 3), characteristic of the fcc structure of metallic Pd.

The peaks at $2\theta = 40°$ correspond to the most intense diffraction line of the (111) plane of metallic palladium. Furthermore, the peaks corresponding to diffraction lines relative to the (200) and (220) planes of Pd[0] were detected only after scale-up at 1.6 kg, when a weak agglomeration of palladium NPs from 2.1 to 3.5 nm was observed (Figure 3B–C). The amorphous nature of 100% MeSiO₁.₅ used as an encapsulating matrix was confirmed by the characteristic wide XRD diffrac-

Figure 1. SEM images at 100 and 250× magnification of Silia*Cat* Pd[0], $d_{50} = 100$ μm. Lab-scale synthesis (top) and 1.6 kg scaled-up synthesis (bottom).

Table 1. TEM and XRD NP size in the Silia*Cat* Pd[0] catalyst used in present study.			
Material	Pd loading [wt %]	Scale-up level [kg]	NP size [nm]
Silia*Cat* Pd[0] (Pd[0]/MeSiO$_{1.5}$)	2.5	0.1 1.6	ca. 2.1 ca. 3.5

tion pattern of the spherical MeSiO$_{1.5}$ xerogel devoid of metal NPs (Figure 3 A).

The Brunauer–Emmett–Teller (BET) and BJH values of specific surface area, pore size, and pore volume of the undoped organosilica support and of the Silia*Cat* Pd[0] catalyst are given in Table 2.

Table 2. Textural properties of the Silia*Cat* Pd[0] catalyst and blank support MeSiO$_{1.5}$.				
Material	Pd loading [wt %]	BET surface area [m^2/g]	Pore volume [cm^3/g]	Pore size [nm]
MeSiO$_{1.5}$	–	865	1.15	5.3
Silia*Cat* Pd[0]	2.5	391	0.82	8.4

The type IV N$_2$ adsorption–desorption isotherms of both materials are typical of mesoporous materials.[26] The organosilica support (Figure 4, left) presents a large BET surface area ($>$ 800 m^2 g^{-1}) and narrow pore-size distribution (6.0 nm) of mesopores capable of adsorbing a large volume of cryogenic nitrogen ($>$ 1.1 cm^3 g^{-1}). On the other hand, the Silia*Cat* Pd[0] catalyst (Figure 4, right) has a lower BET surface area (average 400 m^2 g^{-1}) and a broader pore-size distribution centered at 8.4 nm.

Figure 5 shows the ^{29}Si MAS NMR spectra of the support and of the catalyst. The spectra were analyzed according to the chemical shifts of organotrialkoxysilanes, for which the silicon atoms appear as T^n band type, where n is the number of siloxane bonds of the Si atom.[27] The absence of any signal at −40 ppm related to ethoxy groups derived from non-hydrolyzed MTES, and the presence of signals only at −56 ppm [T^2, MeSi(OSi)$_2$OH] and −66 ppm [T^3, MeSi(OSi)$_3$], corresponds to almost complete hydrolysis of the MTES organosiloxane precursor.[28]

For this study, benzyl alcohol (BA) was examined as a model compound carrying out the hydrogenolysis reaction at 30–70 °C and 3 bar hydrogen pressure. Other BA derivatives such as α-methylbenzyl alcohol (MBA), an intermediate in the production of propylene oxide by the ethylbenzene hydroperoxide-oxidation process, were tested as well. In this process, ethylbenzene is peroxidized to ethylbenzene hydroperoxide (EBHP) in the first step,[29] and then propylene oxide is obtained by the epoxidation of propylene with EBHP. During the epoxidation step, EBHP turns into α-MBA, which can be further hydrogenolysed to ethylbenzene. The hydrogenolysis of MBA is the key step to achieve the recycling process.
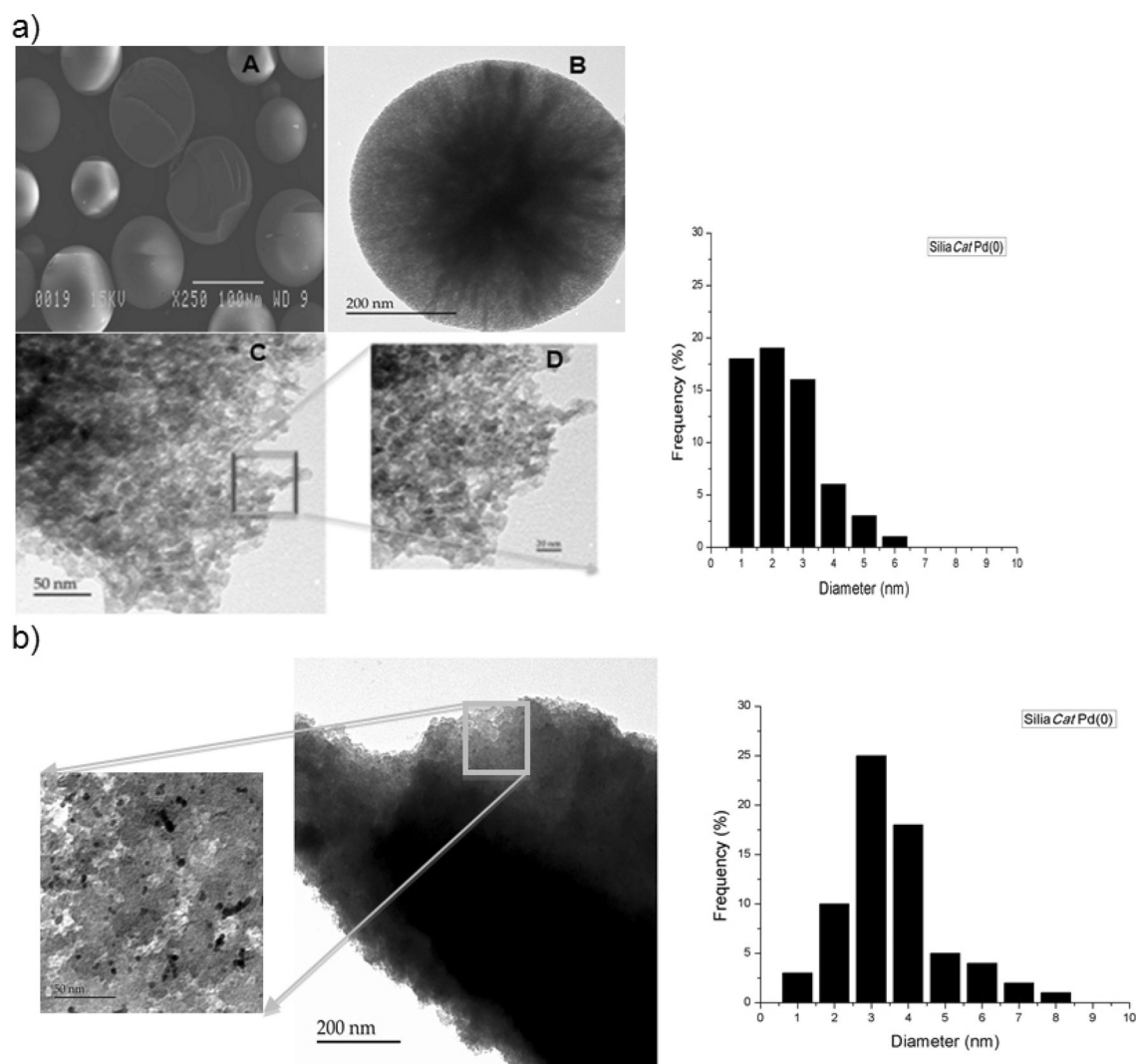
2.1. Effect of Solvent

A series of hydrogenolysis reactions were performed to identify the optimum molar concentration of BA solution in MeOH. The molar concentration of BA in the reaction volume (250 mL) was thus increased from 0.4 to 4 M by charging the 500 mL reactor with 250 mL BA solution from 0.4 M (10.81 g, 100 mmol) to 4.0 M (108.14 g, 1000 mmol) and 0.1 mol % Pd of Silia*Cat* Pd[0]. Table 3 shows the outcomes of the hydrogenolysis under
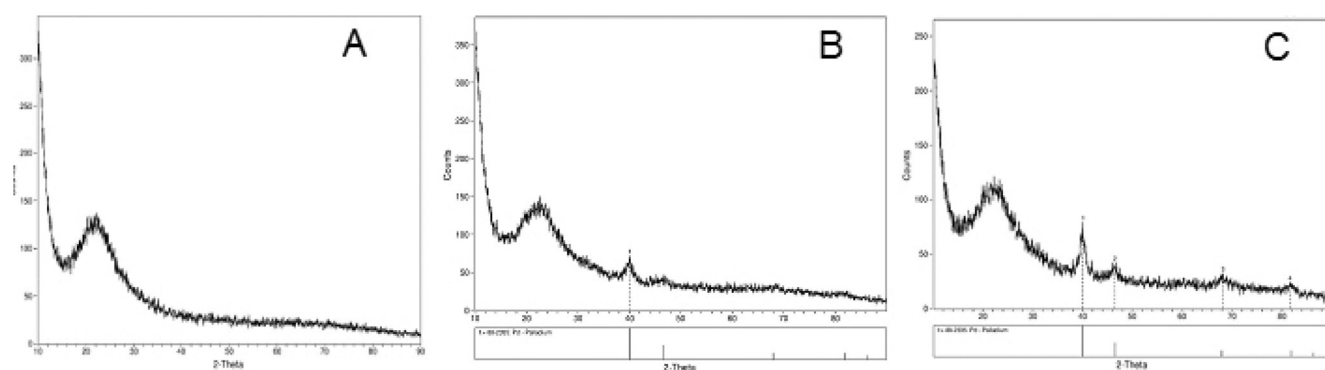
Table 3. Effect of BA concentration in methanol solution in the hydrogenolysis over Silia*Cat* Pd[0].[a]			
Entry	Benzyl alcohol [M]	Time [h]	Toluene yield[b] [%]
1	0.4	1.0 2.0	95 100
2	0.7	1.0 2.0	98 100
3	1.0	0.5 1.0	97 100
4	1.5	0.5 1.0	98 100
5	2.0	0.5 1.0 2.0	73 97 100
6	2.5	0.5 1.0 2.0	62 84 100
7	3.0	1.0 2.0 3.0	65 87 100
8	4.0	3.0 5.0 6.0	77 98 100
[a] Experimental conditions: 0.1 mol % Pd of Silia*Cat* Pd[0] under 3 bar H$_2$, 70 °C. [b] Toluene yield evaluated by GC-MS analysis.			

Figure 2. a) SEM image (A), TEM images (B–D), and palladium particle-size distribution histogram of Silia*Cat* Pd⁰ catalyst (0.1 kg scale-up). b) TEM images and palladium particle-size distribution histogram of Silia*Cat* Pd⁰ catalyst (1.6 kg scale-up).
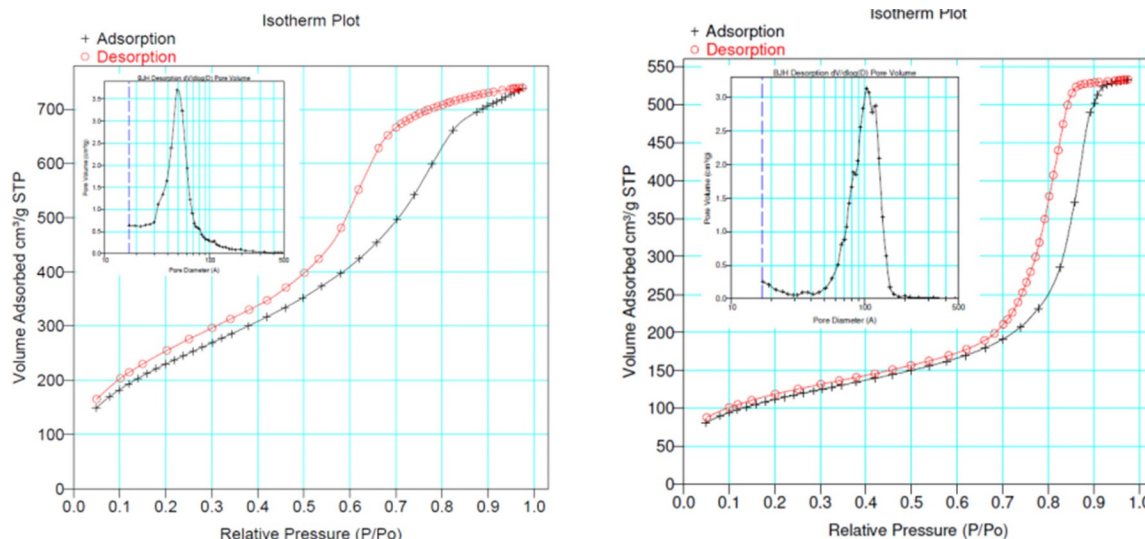

Figure 3. Powder X-ray diffraction (XRD) patterns of MeSiO₁.₅ blank material (A) and Pd⁰ NP-loaded MeSiO₁.₅ organosilica catalyst Silia*Cat* Pd⁰: 0.1 kg scale-up (B); 1.6 kg scale-up (C).

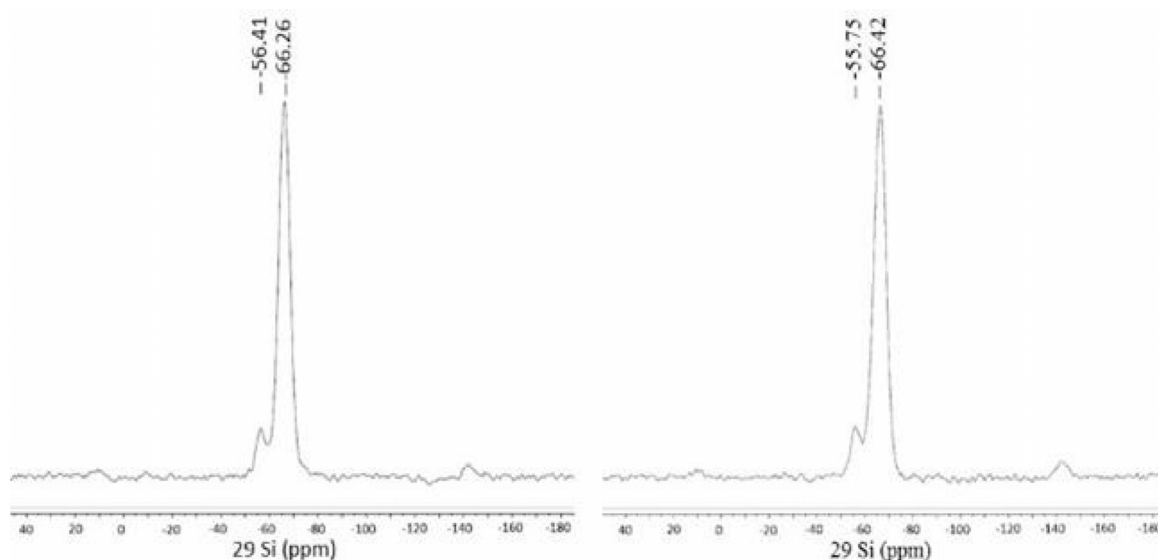3 bar H_2 pressure at 70 °C, over Silia*Cat* Pd⁰ at 0.1 mol% Pd loading (molar ratio of palladium/BA).

Entries 1–2 show that, for both 0.4 and for 0.7 M BA solutions, full conversion to toluene was obtained after 2 h, with almost complete conversion (95–98%) after 1 h only. By increasing the concentration of the substrate solution to 1.0 M and then to 1.5 M, a total conversion to toluene was achieved after 1 h (entries 3 and 4). Further increase of the concentra-

Figure 4. N_2-adsorption and desorption isotherms and BJH desorption pore-size distribution of the amorphous $MeSiO_{1.5}$ support (left) and of the $Pd/MeSiO_{1.5}$ NP organosilica catalyst Silia*Cat* Pd^0(right).
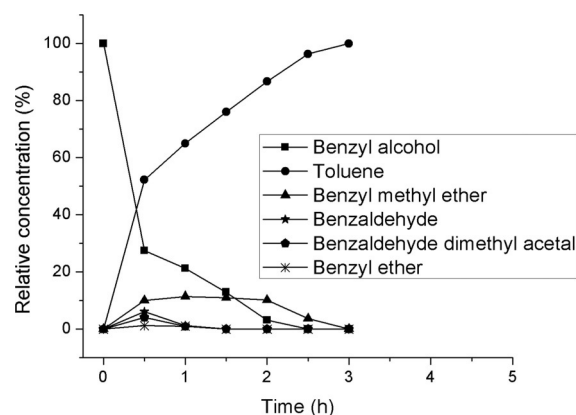

Figure 5. ^{29}Si MAS NMR spectra of the blank support $MeSiO_{1.5}$ (left) and of Silia*Cat* Pd^0 (right).

tion from 3 to 4 M required to extend the reaction time to 3 and 6 h, respectively (entries 5–8).

The GC-MS analysis showed that, in cases in which conversion of BA to toluene was incomplete, a large number of intermediary products of BA such as benzyl methyl ether, benzaldehyde, benzaldehyde dimethyl acetal, and benzyl ether were present in the reaction mixture (Figure 6). However, these intermediary products were completely converted in the final product and no more additional purification is required.

BA solution with a concentration of 1.5 M was used to test other solvents including HPLC grade ethanol, tetrahydrofuran, heptanes, and ethyl acetate (Table 4). The reactions were run again over 0.1 mol% Pd Silia*Cat* Pd^0 at 70 °C under 3 bar H_2 pressure and performed in a 375 mmol BA scale. The 500 mL reactor was charged with 250 mL BA solution (1.5 M; 38.84 mL

Figure 6. Relative concentration of different intermediates formed during the hydrogenolysis reaction of BA in methanol (3 M) over 0.1 mol% Pd of Silia*Cat* Pd^0 versus time.

Table 4. Hydrogenolysis of BA to toluene in different solvents.[a]				
Entry	Solvent	Benzyl alcohol [M]	Time [h]	Toluene yield[b] [%]
1	MeOH	1.5	0.5	97
			1.0	100
2	EtOH[c]	1.5	0.5	99
			1.0	100
3	THF	1.5	0.5	99
			1.0	100
4	heptane	1.5	0.5	97
			1.0	100
5[d]	AcOEt	1.5	0.5	42
			1.0	69
			1.5	97
			2.0	98

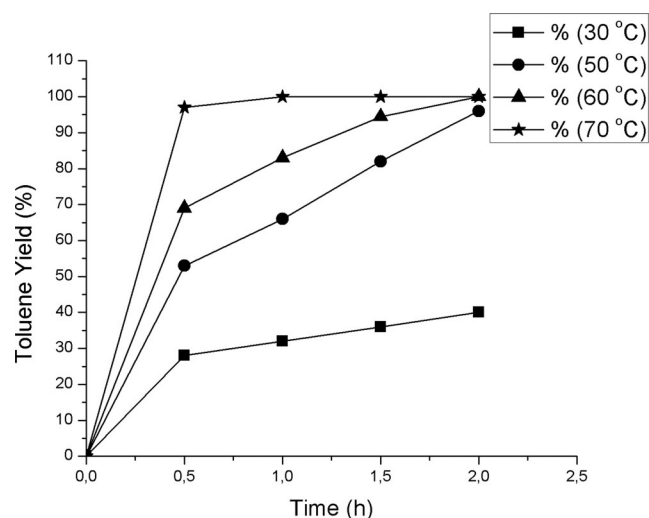[a] Experimental conditions: 0.1 mol% Pd of Silia*Cat* Pd^0, 3 bar H$_2$, 70 °C. [b] Toluene yield evaluated by GC-MS. [c] Anhydrous ethanol was used. [d] Ethylcyclohexane (2%).

of BA in 211.16 mL solvent) and 0.1 mol% Pd (1.56 g Silia*Cat* Pd^0). The variety of solvents ranging in polarity from heptane to EtOH worked well in the Pd-catalyzed hydrogenolysis of BA with quantitative conversion to toluene within 0.5–1 h, except for reaction in EtOAc with complete conversion in only 2 h (entry 5).

2.2. Effect of Reaction Temperature

The effects of reaction temperature on the catalytic activity of Silia*Cat* Pd^0 are shown in Figure 7, in which toluene yield is plotted against the reaction temperature. Reactions were performed over 0.1 mol% Pd of Silia*Cat* Pd^0 using a 1.5 M BA solution in methanol. As expected, the reaction rate increases with increasing reaction temperature. After 1 h reaction, the conversion of BA to toluene increases from 36% at 30 °C to 100% at 70 °C. The reaction temperature should, therefore, be higher than 50 °C in order to obtain a high substrate conversion in short reaction time.

Figure 7. Effect of reaction temperature on the hydrogenolysis of BA to toluene in methanol over 0.1 mol% Pd of Silia*Cat*Pd(0).

2.3. Effect of Reaction Catalyst Loading

By using the conditions developed in entry 1 of Table 4 (375 mmol BA in 250 mL MeOH solution, 1.5 M), the amount of Silia*Cat* Pd^0 spherical catalyst was decreased from 0.2 to 0.025 mol% Pd to assess its catalytic activity. Again, the 500 mL reactor was charged with 250 mL of 1.5 M BA methanol solution (375 mmol BA) and solid Silia*Cat* Pd^0 catalyst (0.24 mmol g^{-1} Pd loading), varying the amount from 0.2 mol% Pd to 0.025 mol% Pd.

Entry 1 in Table 5 shows that the hydrogenolysis of BA over 0.2 mol% Pd proceeds with full conversion to toluene after 15 min only. At lower palladium loading (0.1 mol% Pd), the conversion of BA to toluene was complete after 1 h (entry 2).

Further, decreasing the palladium reaction loading to 0.05 and to 0.025 mol%, the substrate conversion to toluene was complete after 2 and after 6 h, respectively.

Table 5. Effect of catalyst concentration in hydrogenolysis of BA over Silia*Cat* Pd^0.[a]				
Entry	Silia*Cat* Pd^0 loading [mol% Pd][b]	[wt% catalyst][c]	Time [h]	Toluene yield[d] [%]
1	0.2	8	0.25	100
2	0.1	4	0.5	97
			1.0	100
3	0.05	2	0.5	56
			1.0	72
			1.5	84
			2.0	100
4	0.025	1	2.0	51
			4.0	72
			6.0	97

[a] Experimental conditions: 3 bar H$_2$, T = 70 °C. [b] Molar ratio of palladium/BA. [c] Mass ratio of catalyst/BA. [d] Toluene yield evaluated by GC-MS analysis.

2.4. Reaction Scope

A variety of benzylic alcohols and different primary benzylic alcohols containing different functionalities were investigated in the hydrogenolysis reaction (Table 6). Silia*Cat* Pd^0 was thus tested in multigram reactions under 3 bar H$_2$ pressure in methanol (or ethanol) over 0.1 mol% Pd. The yields were evaluated by product isolation or by GC-MS.

The optimized reaction conditions in MeOH at 70 °C developed in Table 4, entry 1, were first applied to hydrogenolysis of a variety of primary (entries 1–8 in Table 5), secondary (entries 6–14), and tertiary benzylic alcohols (entries 15–19) to their corresponding hydrocarbons. Once again, the 500 mL reactor was charged with 250 mL of 1.5 M substrate solution in methanol or in anhydrous ethanol (375 mmol substrate) using the Silia*Cat* Pd^0 spherical catalyst of 0.24 mmol g^{-1} of palladium loading. In these conditions, BA (**1**) was quantitatively reduced to **2** within 1 h (entry 1). Substitution of the phenyl group in the *para* position by electron-donating groups under the same reaction conditions gave the corresponding hydrocarbons in lower yields (entries 2–6 in Table 5). To increase the yield in 4-

Table 6. Hydrogenolysis of different alcohol substrates over SiliaCat Pd[0].[a]

Entry	Benzylic alcohol	Solvent	T [°C]	Product	t [h]	Alcohol conversion[b] [%]	Hydrocarbon yield[b] [%]	Isolated yield [%]
1	**1**	MeOH	70	**2**	0.5	100	97	–
					1	100	100	95
2[c]	**3**	MeOH	70	**4**	1	32	25	
					3	55	43	
					5	74	51	–
3[c]		EtOH	80		1	42	40	
					3	64	63	
					5	79	77	–
4[d]		EtOH	80		1	83	79	–
					3	100	98	96
5[e]	**5**	EtOH	80	**6**	3	100	45	–
					5	100	61	
6[d]		EtOH	80		3	100	69	–
					5	100	97	95
7	**7**	EtOH	80	**8**	3	36	33	–
					5	44	40	
8[d]		EtOH	80		3	53	47	–
					5	75	71	
9	**9**	MeOH	70	**10**	1	70	67	
					3	91	85	
					5	98	91	–
10[f]		EtOH	80		1	90	88	–
					2	100	97	94
11	**11**	MeOH	70	**12**	1	65	62	
					3	85	80	
					5	93	85	–
12[g]		EtOH	80		1	84	82	–
					2	97	92	–
					3	100	96	94
13	**13**	MeOH	70	**14**	1	31	31	
					3	48	47	
					5	59	58	–
14[h]		EtOH	80		1	40	40	
					3	67	66	
					5	91	84	
15[i]	**15**	MeOH	70	**16**	1	76	73	–
					2	100	96	94
16[i]		EtOH	80		1	98	95	–
					2	100	98	96
17[j]	**17**	EtOH[k]	80	**18**	1	75	31	
					3	78	37	
					5	82	40	–
18[d,j]		EtOH[k]	80		3	100	55	–
					5	100	87	–
19		THF[k]	80		5	10	10	–

[a] Experimental conditions: 3 bar H_2, 70–80 °C, catalyst loading = 0.1 mol % Pd. [b] Evaluated by GC-MS. [c] Intermediates observed: 4-methoxybenzyl methyl ether. [d] 0.2 mol % Pd. [e] 4-Aminobenzyl alcohol in 39 % yield. [f] Ethylcyclohexane (3 %). [g] Propylcyclohexane (4 %). [h] Trace of (cyclohexylmethyl)benzene. [i] Presence of isopropylcyclohexane. [j] Intermediates observed: 1,1-diphenylethyl ethyl ether. [k] Molar concentration of 1,1-diphenylethanol solution in anhydrous ethanol or in THF = 1.0 м.

methoxy toluene (**4**), the reactions were carried out in ethanol at 80 °C using 0.1 mol % Pd (entry 3) or 0.2 mol % Pd with quantitative conversion within 3 h (entry 4). Dissolved in ethanol at 80 °C over 0.1 mol % Pd of SiliaCat Pd[0] substrate, 4-nitro-BA (**5**) was quantitatively reduced to 4-aminotoluene (**6**) in 61 % yield and to 4-aminobenzyl alcohol in 39 % yield within

5 h (entry 5). However, the conversion to 4-aminotoluene hydrocarbon over 0.2 mol % Pd of SiliaCat Pd[0] was quantitative after 3 h (entry 6). Entries 7 and 8 show that substitution of the phenyl group in the *para* position by an electron-withdrawing group gave the corresponding hydrocarbon in very poor yield.

Different secondary benzylic alcohols were then tested. α-MBA (**9**) in methanol was reduced to the ethylbenzene (**10**) in 91% yield within 5 h at 70 °C (entry 9) and quantitatively within 2 h in ethanol at 80 °C (entry 10). Substitution of the methyl group in the α-MBA by an ethyl group in 1-phenyl-1-propanol (**11**) or by a phenyl group in diphenylmethanol (**13**) gave the corresponding hydrocarbons in lower yield.

Dissolved in methanol, 1-phenyl-1-propanol (**11**) was reduced to propylbenzene (**12**) in 85% yield within 5 h (entry 11) and quantitatively within 3 h when dissolved in ethanol (entry 12). Diphenylmethanol (**13**) dissolved in methanol at 80 °C was reduced to diphenylmethane (**14**) in 58% yield within 5 h (entry 13) and quantitatively within the same reaction time by carrying out the reaction in ethanol (entry 14). Overall, as expected, these results indicate that the reactivity strongly depends on the aromatic alcohol structure, with the activity of the sol–gel SiliaCat Pd^0 catalyst changing in the order: BA (**1**) > α-methylbnenzyl alcohol (**9**) >1-phenyl-1-propanol (**11**) > diphenylmethanol (**13**).

The steric influence observed on the activity of Pd/MeSiO$_{1.5}$ catalyst can be explained by a mechanism in which the aromatic ring of alcohols is first adsorbed on the Pd nanocrystal surface with the C—O bond lying in close proximity to catalytically active Pd atoms subject to the steric hindrance of the alcohol substrates.[30] Similarly to what happens for the aromatic alcohol hydrogenolysis reaction over Pd/SiO$_2$ and Pd/TiO$_2$ catalysts,[31] the easier reduction of primary (**1**) versus secondary alcohol substrates (**9** or **11**) suggests that, for the unhindered BA (**1**), associative and dissociative hydrogenation mechanisms occurs, whereas the reduction mechanism for secondary alcohols could take place through a radical substitution of the carbon-bonded OH group by a hydrogen atom from the metal surface.

Similar results were obtained when tertiary benzylic alcohols were tested in the hydrogenolysis reaction. Substrate 2-phenyl-2 propanol (**15**) dissolved in methanol at 70 °C was reduced quantitatively to isopropylbenzene (**16**) within 2 h, and also in ethanol at 80 °C (entries 15, 16), whereas the reduction of the more hindered 1,1-diphenylethanol (**17**) in ethanol at 80 °C gave the corresponding hydrocarbon 1,1-diphenylethane (**18**) in 40% yield within 5 h over 0.1 mol% Pd of SiliaCat Pd^0 (entry 17), and in 87% yield when doubling the catalytic amount to 0.2 mol% (entry 18). To avoid the generation of the 1,1-diphenyl-1-ethoxyethane intermediate identified by GC-MS, the reaction was run in tetrahydrofuran at 80 °C. In this solvent 1,1-diphenylethane (**18**) was generated only in 10% yield within 5 h (entry 19). Results for bulky tertiary alcohol substrate indicate that the reactivity once again strongly depends on the aromatic alcohol structure.

2.5. Hydrogenolysis of Carbonyl Compounds

We next studied the heterogeneously catalyzed C═O cleavage reaction of both aryl-substituted aldehydes and ketones over SiliaCat Pd^0 (Table 7). The catalytic hydrogenolysis of aromatic carbonyls to methylene compounds occurs smoothly via the formation of the intermediate BA.[32] Once again, the 500 mL
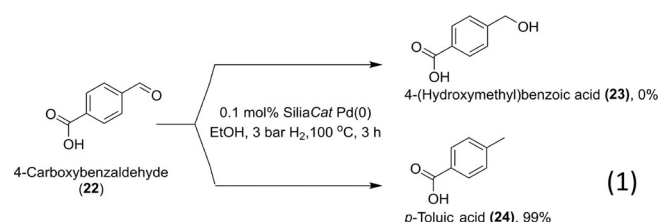
glass reactor was charged with 250 mL of 1.5 M carbonyl compound (375 mmol) solution in anhydrous solvent and 0.1 mol% Pd of SiliaCat Pd catalyst (0.24 mmol g^{-1} Pd loading). In general, the obtained results show that the aromatic carbonyl compounds can readily be converted to the corresponding hydrocarbons in excellent yields over only 0.1 mol% Pd under 3 bar H$_2$ pressure and 70–80 °C. In addition, the reactions were very clean and no chromatographic separation was required to obtain higher purity product.

The hydrogenolysis reaction of benzaldehyde (**19**) and acetophenone (**27**) were first tested in different solvents (entries 1–5 for benzaldehyde and entries 12–15 for acetophenone, in Table 7) such as methanol, ethanol, tetrahydrofuran, and heptane by using the conditions developed for BA in Table 4.

In all solvents tested, the quantitative conversions of benzaldehyde and acetophenone were observed after 1–2 h. The presence of BAs or α-MBA intermediates detected by GC-MS confirmed that the catalytic hydrogenolysis of aromatic carbonyls to hydrocarbon compounds proceeds via the formation of benzylic alcohol intermediates.

Compared to the hydrogenolysis reaction of BA, the catalytic hydrogenolysis of benzaldehyde in different solvents requires longer reaction times. In methanol at 70 °C, the conversion to toluene was quantitative within 5 h while in THF, heptanes, and ethanol the conversion was quantitative in almost 3 h (entries 2–4). A shorter reaction time of 2 h was obtained in ethanol at 80 °C (entry 5).

Substitution of the phenyl group in the *para* position by electron-withdrawing group gave the corresponding hydrocarbons in excellent yields when carrying out the reaction in ethanol at 80 °C over 0.1 mol% Pd catalyst. Methyl 4-formylbenzoate (**20**) was quantitatively reduced (99% yield) within 2 h (entry 6). However, under the same conditions, 4-carboxybenzaldehyde (**22**) was completely converted within 2 h in a mixture of *p*-toluic acid (**24**) and 4-(hydroxymethyl)benzoic acid (**23**) [Eq. (1)], and in benzyl ethyl ether intermediate generated by the presence of EtOH in 24, 65, and 11% yields, respectively (entry 7). When the reaction temperature was increased to 90 °C (entry 8) and further to 100 °C (entry 9), the yield in *p*-toluic acid after 3 h increased to 81% and to 100%, respectively [Eq. (1)]:

4-Carboxybenzaldehyde (**22**) is abundantly obtained in industry as a by-product in the terephthalic acid synthesis, mainly as a precursor to polyethylene terephthalate[33] produced in very large amounts in the ninth largest industrial chemical process.[34] Until now, the main upgrading step in re-

Table 7. Catalytic hydrogenolysis of aldehyde and ketones over Silia*Cat* Pd⁰.[a]

Entry	Carbonyl	Solvent	T [°C]	Hydrocarbon product	t [h]	C=O conversion [%]	Hydrocarbon yield[b] [%]	Alcohol yield[b] [%]	Isolated yield [%]
1[c]	19	MeOH	70	2	1	97	27	36	
					3	100	66	28	–
					5	100	96	0	
2[d]		THF	70		1	85	55	45	–
					2	100	76	24	–
					3	100	97	0	95
3[d]		heptanes	70		1	100	86	8	–
					2	100	88	2	
					3	100	91	0	
4[c]		EtOH	70		1	97	45	27	–
					2	100	79	4	
					3	100	92	0	
5[c]		EtOH	80		1	100	92	0	–
					2	100	98	0	96
6	20	EtOH	80	21	1	100	85	0	–
					2	100	99	0	95
7[f]	22		80	24	1	96	17	67	–
					2	100	24	65	
8[f]		EtOH[g]	90		2	100	60	30	–
					3	100	81	11	
9[f]			100		2	100	95	5	–
					3	100	100	0	99
10[f]	25		80	26	2	91	30	25	–
					4	100	34	28	
11[f]		EtOH	80		2	99	48	11	–
					4	100	62	3	
12[g]	27	MeOH	70	10	1	100	47	41	–
					3	100	82	10	
					5	100	96	0	
13		THF	70		1	100	37	63	–
					3	100	90	10	
					5	100	92	5	
14		heptanes	70		1	72	34	33	–
					3	100	76	24	
					5	100	91	9	
15[f]		EtOH	80		1	100	69	31	–
					2	100	86	14	–
					3	100	98	0	96
16	28	EtOH	80	29	1	98	84	0	–
					3	100	98	0	96
17	30	EtOH	80	31	0.5	99	70	0	–
					1.0	100	75	0	
18	32	EtOH	80	33	1	97	97	0	–
					2	100	99	0	95

[a] Experimental conditions: 3 bar H₂, T = 70–100 °C. [b] Evaluated by GC-MS analysis. [c] Intermediates observed: benzyl methyl ether, benzaldehyde dimethyl acetal, and benzyl ether. [d] Presence of ethylcyclohexane. [g] 4-Carboxybenzaldehyde ethanol solution (1.0 M). [f] Intermediate observed: benzyl ethyl ether. [g] Intermediate observed: benzyl methyl ether.

fining terephthalic acid has been the catalytic hydrogenolysis of 4-carboxybenzaldehyde to *p*-toluic acid over Pd/C or Pd-Ru/C under 14 bar H_2 at 250–270 °C,[35] or over Pd@SiO$_2$ core–shell-particles under 14 bar H_2 at 160–175 °C.[36] Spherical Silia*Cat* Pd^0 has a much better catalytic performance, being capable of catalyzing 4-carboxybenzaldehyde to *p*-toluic acid effectively at 100 °C under 3 bar H_2 in five consecutive cycles without a decrease in catalytic activity, which translates into a significant decrease in the production cost, as well as in the industrial hazard reduction (Figure S1 in the Supporting Information).

Finally, entries 10 and 11 in Table 7 show that substitution of the phenyl group in the *para* position by an electron-donating group gave the corresponding hydrocarbon in lower yield.

Also, the catalytic hydrogenolysis of acetophenone (**27**) in different solvents (entries 12–15) requires longer reaction times when compared to the hydrogenolysis of BA (Table 4), of α-MBA (Table 6, entries 10 and 11), and of benzaldehyde (Table 7, entries 1–6). In methanol, THF, or heptanes at 70 °C under 3 bar H_2 pressure, the conversion to ethylbenzene (**10**) was 90–96% within 5 h (entries 12–14), whereas in EtOH at 80 °C the conversion was quantitative within 3 h (entry 15). Substitution of the phenyl group in the *para* position by electron-donating groups gave the corresponding hydrocarbon in higher yield within 2 h, except for 4′-hydroxyacetophenone (**30**) when only 75% yield was obtained (entries 16–18). When MeOH or EtOH were used as solvents, the GC-MS analysis invariably showed the presence of benzyl alkyl ether, and benzaldehyde dialkyl acetal in the reaction mixture eventually converted in the hydrocarbon final product.

2.6. Catalyst Stability

The reusability of the catalyst was evaluated in several consecutive multigram hydrogenolysis reactions of 375 mmol of BA (40.55 g) dissolved in 250 mL MeOH solution (1.5 M) over 0.1 mol% Pd Silia*Cat* Pd^0 under 3 bar hydrogen pressure at 70 °C. In each consecutive reaction, once the maximum conversion of the BA to toluene was achieved, the catalyst was collected by filtration, extensively washed with THF (×3 during 10 minutes), dried at room temperature, and reused in a subsequent cycle.

Figure 8 shows that the Silia*Cat* Pd^0 heterogeneous catalyst was reused in eight consecutive cycles. In the first four consecutive tests, complete conversion was obtained in 2 h, after which the selectivity to toluene after 2 h decreased, now requiring 3 h to reach very high selectivity values originally obtained in 2 h from the 5th through the 8th reaction run. We ascribe this slight decrease in activity to weak agglomeration of palladium NPs from 2.1 nm to average 6 nm after eight consecutive experiments, as determined by the TEM image (Figure 9).

The spherical Silia*Cat* Pd^0 catalyst, indeed, is stable and robust, as shown by the SEM images (Figure S2 in the Supporting Information) and the N_2 adsorption isotherms (Figure S3 in the Supporting Information) before the 1st and after the 8th reaction run.
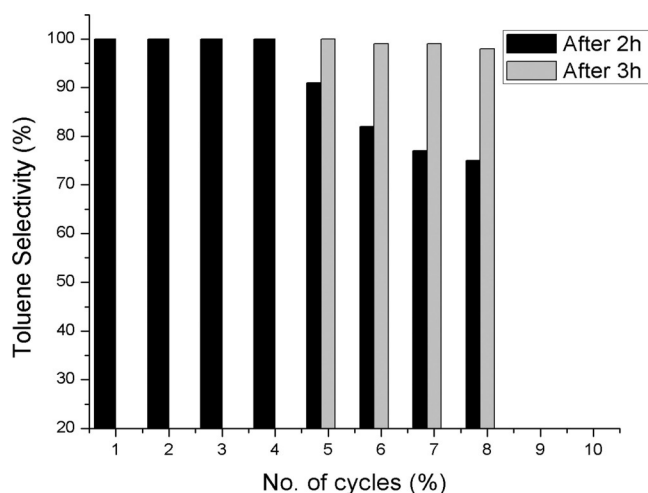

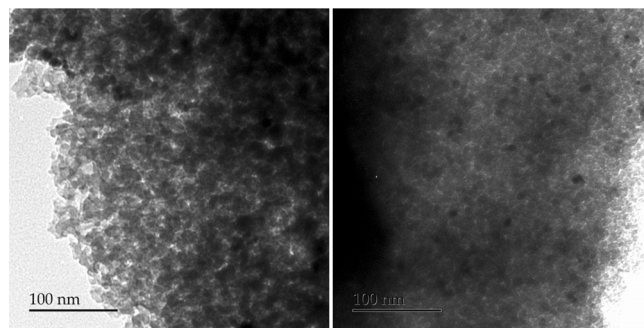**Figure 8.** Reusability of Silia*Cat* Pd^0 in the hydrogenolysis of BA.

Figure 9. TEM images of the Silia*Cat* Pd^0 NP organosilica before (left) and after the eighth reaction run (right).

The amounts of Pd and Si leached from the Silia*Cat* Pd^0 during catalysis in the isolated crude product are presented in Table S1 in the Supporting Information, which were obtained under different conditions after filtration of the catalyst through ICP-OES,[37] and are extremely low. In detail, the amount of leached Pd never exceeds 3 ppm, and neither does that of Si with the exception (for the latter metal only) of 1,1-diphenylethanol (entry 7), and for ketones 4′-methoxyacetophenone (entry 12) and 4′-methylacetophenone (entry 14), which are somehow able to extract the metal from the organosilica surface.

2.7. Silia*Cat* Pd^0 versus Different Heterogeneous Pd Catalysts

The optimal reaction conditions developed for the hydrogenolysis reaction of BA over Silia*Cat* Pd^0 (0.1 mol% Pd, 70 °C, 3 bar H_2 on a 375 mmol scale in the 500 mL reactor) were used to compare the catalytic activity of the latter material with that of different commercial solid palladium catalysts including Pd/C, ROYER catalyst, Pd Escat 1351, as well as with an organically modified aluminosilicate (2.1 wt% Pd^0/MeSiO$_{1.5}$-Al$_2$O$_3$,) made by our group (unpublished results). The textural properties of the

Table 8. Textural properties of different palladium heterogeneous catalysts.

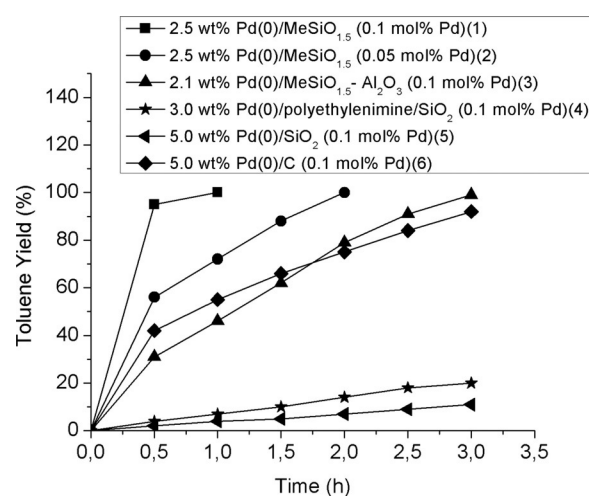| Entry	Catalyst	Pd loading [wt%]	Particle size [μm]	BET surface area [$m^2 g^{-1}$]	Total pore volume [$mL g^{-1}$]	Average pore size [nm]
1	Pd^0/MeSiO$_{1.5}$ SiliaCat Pd^0	2.5	$d_{50}=100$ $d_{90/10}=2$	402	0.80	8.0
2	Pd^0/MeSiO$_{1.5}$-Al$_2$O$_3$	2.1	$d_{50}=100$ $d_{90/10}=2$	613	0.70	4.6
3	Pd^0/polyethylenimine/SiO$_2$ ROYER Pd catalyst	3.0	$d_{50}=111$ $d_{90/10}=18$	234	0.2	4.7
4	Pd/SiO$_2$ Pd Escat^{TM} 1351	5.0	$d_{50}=43$ $d_{90/10}=6$	144	0.97	27
5	Pd/C	5.0	$d_{50}=18$ $d_{90/10}=34$	596	0.61	4.1

heterogeneous catalyst used in this study are presented in Table 8.

Invariably (Figure 10), the SiliaCat Pd^0 showed much higher catalytic activity with complete conversion of BA to toluene after 1 h only over 0.1 mol% Pd and after 2 h over 0.05 mol% Pd (Table 9, entries 1 and 2).

The organically modified aluminosilicate 2.1 wt% Pd^0/MeSiO$_{1.5}$-Al$_2$O$_3$ was the second best catalyst, with complete BA conversion after 3 h (entry 3 in Table 9).

Under the conditions specified above, the only commercial catalyst showing reasonable activity was the 5 wt% Pd/C catalyst, affording full conversion of BA to toluene after 5 h. Both Pd/SiO$_2$ (entry 4) and Pd^0/polyethylenimine/SiO$_2$ (entry 5) showed modest activity with 11 and 20% yield after 3 h, respectively.

We ascribe the high catalytic activity of the SiliaCat Pd catalyst in the BA hydrogenolysis reaction to its spherical morphology, as well as to the hydrophobic nature of the spherical organosilica material that prevents the accumulation of water formed during the reaction. Excellent robustness and mechanical stability add to the well-known chemical stability of methylsilica, with the spherical catalyst contributing excellent stability to the catalytic activity.

Figure 10. Benzyl alcohol hydrogenolysis to toluene mediated by different palladium solid catalysts.

3. Conclusions

The hybrid sol–gel SiliaCat Pd^0 material with a spherical morphology is a highly selective mediator for the hydrogenolysis

Table 9. Hydrogenolysis reaction of BA over different heterogeneous catalysts.[a]

Entry	Catalyst	Pd reaction loading[b] Pd [mol%]	Catalyst [wt%]	t [h]	Yield[c] [%]	Isolated yield [%]	Leaching (mg/kg)[d] Pd	Si
1	2.5 wt% Pd^0/MeSiO$_{1.5}$ SiliaCat Pd^0	0.1	4	0.5	95	–	1.07	1.11
				1	100	95		
2		0.05	2	0.5	60	–	1.39	0.88
				1	72	96		
				2	100			
3	2.1 wt% Pd^0/MeSiO$_{1.5}$-Al$_2$O$_3$	0.1	5	2	79	–	1.75	0.14
				3	99	96		
4	5 wt% Pd/SiO$_2$ Pd Escat^{TM} 1351	0.1	2	1	4	–	1.49	1.85
				3	11			
5	3 wt% Pd^0/polyethylenimine/SiO$_2$ ROYER Pd catalyst	0.1	3.3	1	7	–	1.63	1.07
				3	20			
6	5 wt% Pd/C	0.1	2	1	55	–	1.47	0
				3	92	–		
				5	98	92		

[a] Experimental conditions: 0.1 mol% Pd, 70°C, 3 bar H$_2$. [b] Pd/BA mass and molar ratio. [c] Yield evaluated by GC-MS. [d] Leaching of Pd and Si by ICP-OES.

of a large variety of aromatic alcohols, aldehydes, and ketones under mild conditions (70 °C, 3 bar H_2), requiring an ultralow (0.1 mol % Pd) catalytic amount. Adding practical relevance to these findings, the catalyst is highly stable, retaining its catalytic activity for numerous consecutive runs. Finally, the catalytic performance of this new material is significantly better than that of several commercial palladium catalysts, including Pd/C and Pd/SiO_2.

These results provide chemical industry and research laboratories with a new, clean, and efficient methodology for the reductive deoxygenation of alcohols and carbonyl compounds. The process is of high synthetic relevance to both the fine chemical and petrochemical industries. For example, 4-carboxybenzaldehyde is obtained in huge amounts as a by-product of terephthalic acid synthesis[33] in the ninth largest petrochemical industrial chemical process.[34] Refinement of terephthalic acid involves the catalytic hydrogenolysis of 4-carboxybenzaldehyde to *p*-toluic acid, which, so far, has been conducted in industry over Pd/C or Pd-Ru/C under 14 bar H_2 at 250–270 °C or over Pd@SiO_2 under 14 bar H_2 at 160–175 °C.

In 2013,[38] we anticipated that catalysts with spherical morphology were going to provide a long-awaited new generation of sol–gel catalysts.[39] Following the first study devoted to solvent-free squalene hydrogenation,[21] this study supports the above prediction for the important hydrogenolysis reaction class. New studies reporting the performance of this new class of materials in numerous reactions successfully mediated by Pd NPs, including the most important conversions in synthetic organic chemistry, namely the C—C cross-coupling reactions,[40] are underway.

Conflict of Interest

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