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Cyclodextrin-grafted silica supported Pd nanoparticles: an efficient and versatile catalyst for ligand free C-C coupling and hydrogenation

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Abstract: Silica is an extremely versatile support which is capable of hosting metal NPs and enhancing their stability and reactivity. In this study, a novel Pd supported cyclodextrin/silica support, which we have denoted PdNPs/Si-CD, has been prepared. The highly efficient and homogeneous impregnation of small palladium nanoparticles in this support has been carried out under conventional conditions, while ultrasound irradiation has a beneficial effect on catalyst preparation. The catalyst has exhibited excellent activity in ligand free C-C Suzuki end Heck couplings over a large number of aryl iodide and bromides, while MW irradiation use cuts down reaction time. PdNPs/Si-CD have shown high activity and selectivity in the hydrogenation reaction, while the semihydrogenation of phenylacetylene was studied with excellent results.

Introduction

The discovery, in the late 1980's by Haruta *et al.*, that α -Fe₂O₃ supported Au nanoparticles of smaller than 5 nm are very active in CO oxidations caused the catalysis community to realize the significance that size has on catalytic properties.^{1,2} The high surface energy of these particles makes them extremely reactive meaning that most systems undergo aggregation without protection or surface passivation.³ Whereas it is well known that nanosize in catalysis is important because of high surface areas and reactivities, the mechanistic insight of a nanocatalyst is not so obvious. Several other key catalyst parameters need to be considered. These include nanoparticle shape and any synergic effects that may exist between metal and support.⁴ Nanoparticles (NPs) have been so far been synthesized using various chemical and physical methods.⁵ The preparation of NPs frequently involves the reduction of metal ions in solutions or in high temperature gaseous environments meaning that not only has the search for new nanocatalysts been a focus of interest but even

the optimization of metallic NP green syntheses has attracted significant attention from the scientific community.⁶ Palladium catalysts have emerged as powerful and versatile tools in organic synthesis.⁷ A number of palladium catalysts are commercially available and, interestingly, their reactivity, stability and selectivity can be tuned by ligands⁸ (phosphines, carbenes, amines, etc.) and/or additives⁹. Although ligand containing molecular palladium catalysts, have long proven to be efficient and very popular,¹⁰ continuous investigation into "green", so-called "ligandless", palladium catalysts is ongoing.¹¹ Phosphine free C-C coupling reactions may involve the presence of nanosized Pd-colloids as suggested by Reetz *et al.*. In fact, Bonneman *et al.*¹² observed in 1991 that they are generated from Pd(II) salts in polar solvents in the presence of tetraalkylammonium salts at high temperatures.¹³ PdNPs have now become a valuable alternative and provide several "green" chemistry benefits.¹⁴ One of the principle advantages that these systems present is the fact that they are catalytically active in low amounts driving interest from industry in this field. Recent years have thus seen various syntheses being scaled up to the kilogram scale.¹⁵ De Vries,¹⁶ has detailed PdNPs' role as a source of Pd atoms that detach from the surface during oxidative addition and undergo highly efficient turnover in solution. At high temperature, PdNPs are stabilized by the presence of polar solvents or ammonium salts and ionic liquids that influence PdNP dimensions and favour productive reactions¹⁷. Heterogeneous supports also provide a valuable influence on reaction outcome. Many studies have validated the use of Pd colloids in Heck reactions, although reactions with less reactive aryl bromides have not been very successful in the absence of stabilizers, such as ammonium salts, or ligands.

Silica is an extremely versatile support and one which is capable of hosting metal NPs, enhancing their stability and reactivity¹⁸. Silica has found widespread use in the preparation of solid supported PdNPs because of the benefits that it provides, which include excellent stability (chemical and thermal), mechanical robustness, good accessibility and porosity. In fact, a number of organic-inorganic hybrid materials have seen extensive use in the design of novel catalytic systems.¹⁹ Our recent study into the efficient grafting of cyclodextrin (CD) into an inorganic silica framework provided a material which showed a hydrophilic/hydrophobic profile and surface reactivity which were modified with respect to material bulk properties.²⁰ To the best of our knowledge, only one manuscript has so far reported the use of a CD-silica derivative in the preparation of a heterogeneous PdNP catalyst and its subsequent Heck reaction.²¹ This work therefore aims to exploit our experience in CD synthesis to explore this field further.²²

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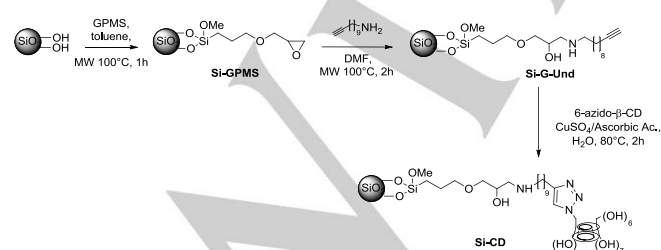
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We herein report the preparation of a new PdNP catalyst which attempts to amalgamate the properties of an amino alcoholic branched spacer and a triazolyl- β -CD derivative to effectively immobilize and stabilize PdNPs. Our intention here is to produce an extremely versatile catalyst and explore its potential over a series of hydrogenations and coupling reactions, such as Suzuki, Heck and Sonogashira, which are ranked among the most general transformations in organic synthesis.

Scientists have recently devoted a great deal of research to designing more environmentally sound and low impact protocols to operate under non conventional conditions.²³ Solvent-free and aqueous media reactions, NPs, microwave assisted and ultrasound promoted syntheses are all key developments in the design of greener protocols. Sonochemistry has been very reliably employed in the synthesis of small, high production yield NPs, while the selective heating of catalytically active metal species under microwave irradiation is currently generating significant interest.²⁴ The objective of this manuscript is to investigate the efficacy of ultrasound irradiation in the preparation of Pd/Si-CD hybrid system supported PdNPs. Non-conventional MW irradiation has also been used to optimize the synthetic procedure for high reaction yields in short reaction times. All protocols were designed to operate without a stabilizer (ammonium salts or ionic liquid) and be ligand and free so as to fulfil green chemistry criteria.

Results and Discussion

The silica derivative consists of β -CD anchored to silica via an alkyl hydroxyl amino spacer (Scheme 1). The Silica was derivatized with 3-glycidoxypropyltrimethoxysilane (GPMS) that was then reacted with 10-undecynyl-1-amine (Und) to open the epoxide ring. The Si-CD derivative was finally obtained from a Cu-catalyzed azide-alkyne cycloaddition (CuAAC) with 6-monoazido-6-deoxy- β -CD. The synthetic protocol can be performed either under MW irradiation or via mechanochemical activation as already described in a previous study.²⁰ All samples were extensively characterized by TGA, elemental analysis, IR, BET and HRTEM. A highest final loading of 135 $\mu\text{mol/g}$ of β -CD was measured when all three steps were performed under MW irradiation.²⁰



Scheme 1. Synthetic scheme for the preparation of Si-CD.

PdNPs were immobilized on the Si-CD via the reduction of the $\text{Pd}(\text{OAc})_2$ precursor in ethanol or in water. The procedure was repeated at room temperature and at reflux. The reaction was monitored via the colour change in the silica support.

The reaction from Si-G-Und afforded a light grey silica derivative, while all the other attempts with Si-CD furnished a dark grey solid. ICP analyses confirmed that Pd content was lower, 2.3 Pd (%wt), when CD was absent from the silica support (See Table 1, entry 1-4). Pd content in the Si-CD samples was in the 4.7 to 6% range and the highest amount was achieved when the loading was performed in ethanol at reflux. Ultrasound irradiation of the $\text{Pd}(\text{OAc})_2$ solution in ethanol with Si-CD afforded 4.7% Pd.

Table 1. Preparation conditions and Pd wt% content of the various supported Pd catalysts.

Entry (sample name)	Starting Silica deriv.	Reaction condition ^[a]	Pd content ^[b] wt%	Particle size ^[c] (nm)
1 (Pd/Si-Und)	Si-G-Und	EtOH, Reflux, 2h	2.3	n.d.
2 (Pd/Si-CD (A))	Si-CD	EtOH, r.t., 48 h	4.75 %	14.7
3 (Pd/Si-CD (B))	Si-CD	EtOH, reflux 2h	6.0% (5.95) ^[d]	5.4 (6.2) ^[e]
4 (Pd/Si-CD (C))	Si-CD	H ₂ O, 80°C 2h	4.88	14.1
5 (Pd/Si-CD (US))	Si-CD	EtOH, US, 2h	4.7%	4.0 ^[e]

[a] All reactions were performed in the presence of $\text{Pd}(\text{OAc})_2$ 400 $\mu\text{mol/g}$; [b] Determined by inductively coupled plasma analysis (ICP); [c] Average particle size of Pd particles was measured on the basis of TEM images; [d] data measured on the catalyst after a first usage; [e] the particle size was measured by XRD.

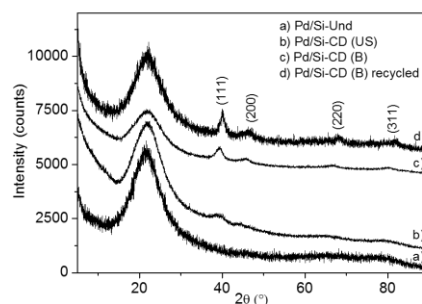


Figure 1 XRD patterns measured on samples listed in Table 1: a) Pd/ Si-Und; b) Pd/Si-CD (US); c) Pd/Si-CD (B) and d) recycled Pd/Si-CD (B).

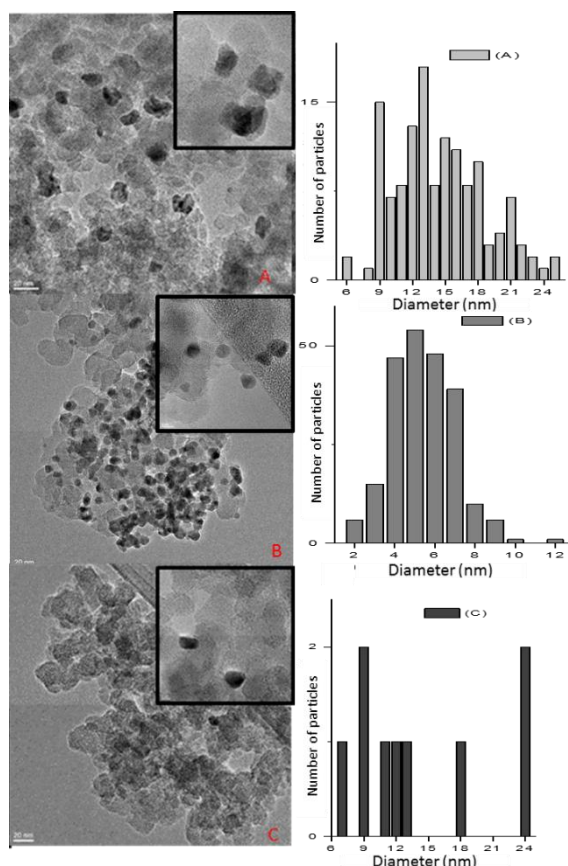


Figure 2. TEM images of Pd/Si-CD catalyst A) Pd/Si-CD (A): sample was prepared in EtOH at r.t. (Table 1 Entry 2); B) Pd/Si-CD (B): sample was prepared in EtOH at reflux (Table 1, Entry 3) C) Pd/Si-CD (C): sample was prepared in water at 80°C entry 4 Table 1. Pd particle size distributions measured on the same samples are also reported.

The catalysts' XRD patterns show that PdNPs exist on the Pd/Si-CD substrates (Figure 1, curves c). The strongest peak in the XRD pattern (21.86°) is the typical diffused scattering of the amorphous SiO_2 support. The other weaker and broader peaks are indexed as the (111), (200), (220), and (311) planes of the PdNPs (cubic phase, JCPDS 46-1043). A slight shift in 2θ values is observed, with respect to standard references, in all peaks, which suggests that a small increase in crystallite d-spacing occurs as a consequence of particle nanosize. These peaks are absent in the sample that was prepared without CD (sample Pd/Si-Und, curve a). Average crystallite size, estimated using the Scherrer formula, is 6.2 nm for sample B and 4.0 nm for sample prepared in the ultrasound bath.

TEM images of the catalyst are shown in Figure 2. Pd/Si-CD samples A and C, which were prepared in ethanol at r.t. and water at 80 °C respectively, consist of non-uniform (mainly spheroidal) particles with a diameter range of 6 to 25 nm (Figure 1, examples A and C). Pd particle size distributions of the same materials are also reported in Figure 2. A larger number of particles were measured in sample A (135), while only a few (9) were detected in sample C meaning that no statistical considerations can be

made in this case. Sample A particles are found most abundantly at 9 and 13 nm. By contrast, Pd particles were present in larger amounts, were smaller and more uniformly distributed (distribution centred around 5 nm, Figure 2 sample B) when the sample was refluxed in ethanol for 1hrs. TEM and XRD data were in accordance.

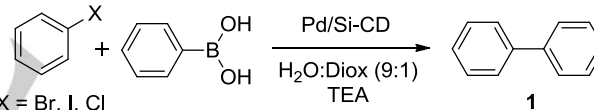
The above mentioned analyses show that the presence of CD plays a crucial role in influencing Pd content and PdNP size distribution. The amino alcohol on the Si-G-Und intermediate can coordinate Pd species, but only on the Si-CD derivative were PdNPs loaded in reasonable amounts. Solvent choice and reaction temperature also influenced NP size distribution on the silica. The smallest NPs were produced under US irradiation.

The Suzuki–Miyaura reaction was tested first as the applicability of the new catalyst was investigated (Table 1). The study initially focused on the optimization of a phenyl boronic acid and halo benzene model reaction. These reactions were performed in a $\text{H}_2\text{O}/\text{dioxane}$ 9:1 mixture with the aim of following green principles. The study aimed to optimise reaction conditions in terms of lowest catalyst amount and shortest reaction time. As depicted in Table 1, we compared conventional conditions to MW irradiation as we maximized the catalytic performances of PdNPs/Si-CD.

Complete conversion was obtained with iodobenzene and bromobenzene under conventional conditions with 0.2% Pd after 4 h heating at 100°C. MW irradiation enabled Pd amount to be decreased to 0.05 mol % while reducing reaction time to 30 min. 8-9% of starting material was unreacted after 15 min.

Table 1. Suzuki-Miyaura Optimization^[a]

Entry	X	Reaction Conditions ^[a]	Si-CD-Pd cat.	Yield (conv.) %
1	I	o.b., 100 °C, 4 h	0.5 mol %	98 (>99)
2	I	o.b., 100 °C, 4 h	0.2 mol %	98 (>99)
3	I	MW, 100 °C, 1 h	0.5 mol%	99 (>99)
4	I	MW, 100 °C, 1 h	0.2 mol%	98 (>99)
5	I	MW, 100 °C, 1 h	0.1 mol %	97 (>99)
6	I	MW, 100 °C, 30'	0.2 mol %	96 (>99)
7	I	MW, 100 °C, 15'	0.2 mol %	91 (92)
8	I	MW, 100 °C, 30'	0.1 mol %	98(>99)
9	I	MW, 100 °C, 30'	0.05 mol %	96(>99)
10	I	MW, 100 °C, 15'	0.1 mol %	90 (91)
11	Br	o.b., 100 °C, 4 h	0.5 mol %	98 (>99)
12	Br	o.b., 100 °C, 4 h	0.2 mol %	98 (>99)
13	Br	MW, 100 °C, 1 h	0.2 mol %	98(>99)



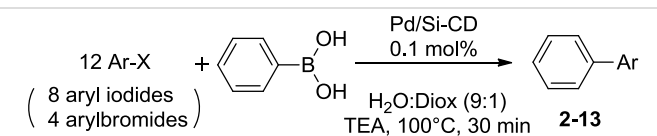
FULL PAPER

14	Br	MW, 100 °C, 1 h	0.1 mol %	100 (>99)
15	Br	MW, 100 °C, 30'	0.2 mol %	99(>99)
16	Br	MW, 100 °C, 30'	0.1 mol %	99 (>99)
17	Br	MW, 100 °C, 30'	0.05 mol %	98(>99)

[a] all reactions were performed in H₂O:Dioxane 9:1, 1 eq. aryl-X, 1.1 eq boronic acid, 2 eq. TEA

An array of twelve aryl halides, both electron-rich and electron-deficient, was chosen as Suzuki–Miyaura cross-coupling reaction substrates and phenyl boronic acid was used for further investigations of Pd/Si-CD catalytic performance (Table 2).

Table 2. Scope of Suzuki–Miyaura cross-coupling reactions



Entry	Ar-X	Product #	Yield ^[a]
1		2	94
2		3	98
3		4	98
4		5	>99 ^[b]
5		6	95
6		7	78 ^[c]
7		8	61
8		9	99 ^[b]
9		10	94 ^[c]

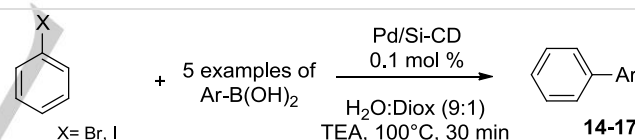
10		11	90
11		12	99 ^[c]
12		13	99 ^[b]

[a] reaction performed in H₂O:Dioxane 9:1, 1 eq. aryl-X, 1.1 eq. boronic acid, 2 eq. TEA, 0.2% mol Pd, [b] reaction performed with 0.2% mol Pd; [c] reaction performed with 0.5% mol Pd

The reaction was performed with 0.1 mol % Pd at 100°C for 30 min and yields of 61–99% were achieved. Reaction outcomes showed good aryl iodide and bromide reactivity, while high yields were obtained even in presence of high steric hindrance (Entry 4, 5, 7, 9 Table 2). The high reaction rate enabled the ethyl 4-iodobenzoate to be selectively converted to the diphenyl derivative in water without hydrolysing the ester moiety (entry 1, Table 2).

The optimized protocol was used in screening a set of 4 boronic acids with iodo and bromo benzene giving yields of 88 to 99 (Table 3). 2,5-dimethoxy phenyl boronic acid surprisingly reacted in 30 min at 100°C to give 97 and 88% yields with iodo and bromo benzene respectively.

Table 3. Suzuki–Miyaura cross-coupling reaction of iodo and bromo benzene with phenylboronic acid derivatives in aqueous media^[a]



Entry	Halobenzene	Boronic acid	Product	Yield
1	Ph-I		14	99
2	Ph-Br		14	98
3	Ph-I		15	98
4	Ph-Br		15	97
5	Ph-I		16	97
6	Ph-Br		16	88
7	Ph-I		17	99
8	Ph-Br		17	98

[a] reaction performed in H₂O:Dioxane 9:1, 1 eq. iodo or bromo benzene, 1.1 eq. boronic acid, 2 eq. TEA, 0.1% mol Pd.

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The abovementioned results prompted us to continue with a study of Pd/Si-CD catalytic activity in the Heck reaction. A series of reactions were performed using varying conditions for the sake of optimizing the protocol.

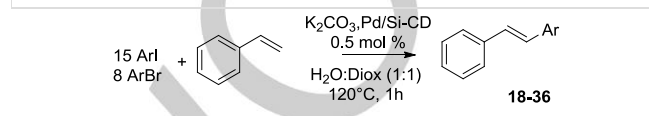
Table 4. Heck Optimization


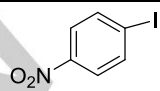


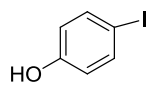

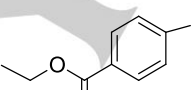
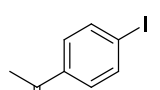
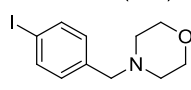


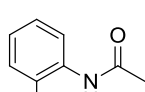
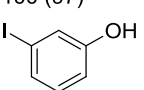
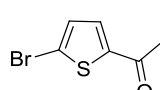
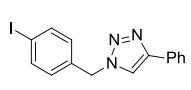
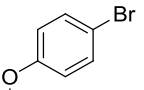

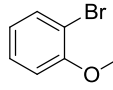

Entry	R	Solvent	Reaction Conditions ^[a]	Si-CD-Pd mol %	Yield % (conv)
1	H	DMF	Et ₃ N o.b., 110°C, o.n.	1	52 (60)
2	H	H ₂ O:Diox 1:1	K ₂ CO ₃ o.b., 90°C, o.n.	1	98 (>99)
3	H	H ₂ O:Diox 1:1	K ₂ CO ₃ o.b., 90°C, 4h.	1	98 (>99)
4	H	H ₂ O:Diox 1:1	K ₂ CO ₃ o.b., 90°C, 4 h	0.5	98 (>99)
5	H	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 4h	1	96 (>99)
6	H	DMF	Et ₃ N, MW., 120°C, 4h	1	87 (>99)
7	H	DMF	K ₂ CO ₃ , MW., 120°C, 4h	1	85 (98)
8	H	H ₂ O:Diox 1:1	Et ₃ N, MW., 120°C, 4h	1	34 (56)
9	H	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 1h	1	99 (>99)
10	H	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 30 min	1	87 (90)
11	H	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 1h	0.5	97 (>99)
12	H	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 1h	0.2	89 (95)
13	OMe	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 1h	1 %	66 (84)
14	OMe	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 1h	0.5	71 (76)
15	OMe	H ₂ O:Diox 1:1	K ₂ CO ₃ , MW, 120°C, 1h	0.2	62 (68)

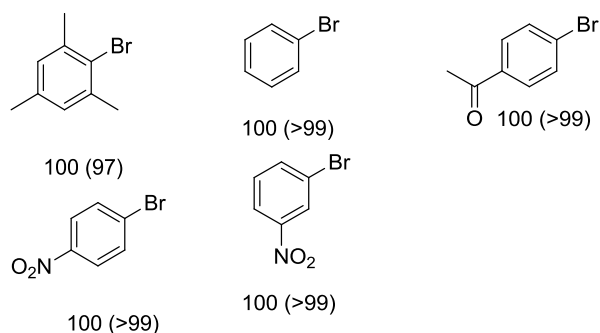
[a] reactions performed with 1.25 eq. styrene, 2 eq. of base

The model substrates for the initial screening were phenyl iodide and styrene leading to stilbene. As summarized in Table 4, Pd/Si-CD quantitatively converted the starting material under

conventional conditions in 4 h at reflux in Dioxane:H₂O 1:1 (Table 4 entry 1-4). The reaction was successful with K₂CO₃ as a base and 0.5 mol % of Pd. MW irradiation sped up the reaction and full conversion was obtained after 1h, while catalyst amount was reduced to 0.2 mol % (Table 4, Entry 11-12). Excellent results were also achieved in DMF with K₂CO₃ as a base (Table 4, Entry 7). A slight decrease in yield was observed when optimized protocols were performed with 4-iodoanisole.

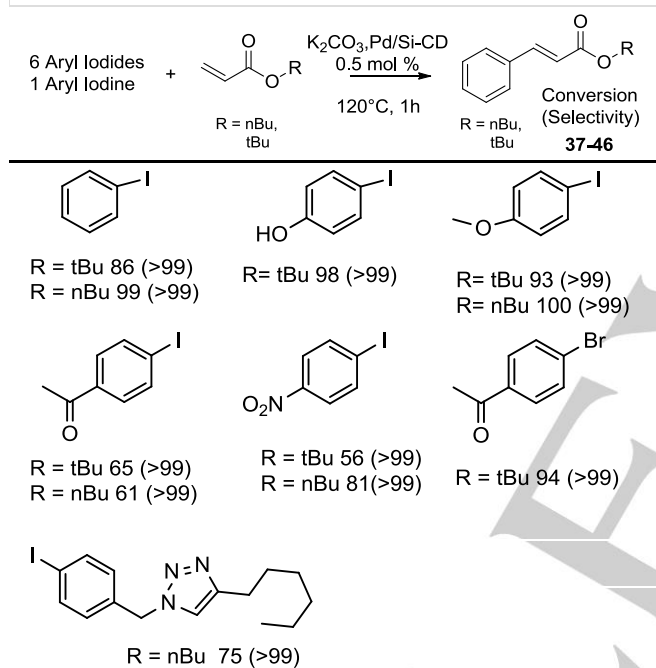
Table 5. Scope of the Heck reaction with different aryl iodides and bromides and styrene^[a]


		
100 (>99)	100 (>99)	100 (98)
		
100 (97)	100 (98)	88 (>99)
		
100 (96) ^b	100 (>99)	100 (98)
		
100 (97)	100 (95)	100 (>99)
		
100 (99)	33 (>99)	34 (100)
		
100 (100)	100 (96)	100 (97)



[a] The reactions were performed in H₂O:Dioxane 1:1, 1.25 eq. styrene, 2 eq. K₂CO₃, 0.5% mol Pd, 120 °C, 1 h [b] the reaction was in DMF

Table 6. Scope of the Heck reaction with different aryl iodides and bromides and butylacrylate.^[a]



[a] reactions performed with 1.25 eq. acrylate, 2 eq. K₂CO₃, 0.5% mol Pd, 120 °C, 1 h. the solvent was H₂O:Dioxane 1:1 for the reaction with *t*-butyl acrylate; while DMF was chosen for *n*-butyl acrylate.

In order to gauge the versatility of this protocol, a large number of substrates were screened in parallel using the MW reactor (SynthWave by Milestone) which is well suited to parallel syntheses at any reaction temperature and gas pressure (up to 300 °C and 200 bar). Aryl bromides and iodides with electron-withdrawing and electron-donating substituents were reacted with styrene, *n*-Butyl and *tert*-Butyl acrylate. Excellent results were obtained in 1 h with 0.5 mol % Pd without the addition of ligands and the reactions almost always gave quantitative yields (see Table 5 and 6). Triazolyl and thiazole iodo derivatives were included in the list of reagents, as representative of heterocyclic compounds, and yielded the desired product in the 34 to 75 % yield range.

The regiochemical outcome of the Heck reaction with unsymmetrical olefins is of utmost importance and so Tables 5 and

6 not only indicate conversion, but also selectivity. While acrylates showed >99% selectivity, the styrene gave a slight decrease. Regiochemistry was influenced by steric and electronic factors: sterically hindered and electron rich halides showed selectivities in the 98-95% range, while all the other experiments only furnished the desired regioisomer. As depicted in Figure 3, the α -substituted regioisomer was the main side product when a mixture of isomers was observed. α -substitution products were present in the 1-3% range, while the β -cis regioisomer was detected at 0.5 % when the reaction was performed with halo anisoles, iodophenol, 2-methyl iodobenzene, 2,5 dimethyl halobenzenes and 2-amino iodobenzene.

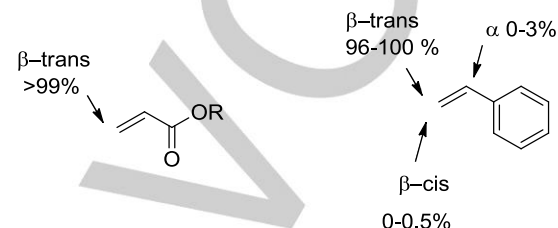
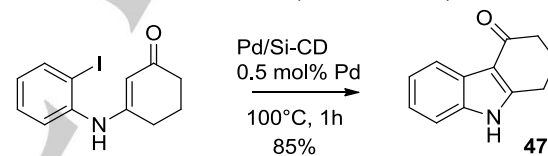


Figure 3. Ligand-free Heck reaction: observed range of selectivity.

An example of the intramolecular ligand free Heck reaction²⁵ was also successfully performed to display the high reactivity of this catalyst. The carbazole derivative was obtained in 85% after 1 h at 100 °C with 0.5 mol% Pd. (see Scheme 2)



Scheme 2. Intramolecular Heck reaction

Pd/Si-CD reusability was also checked (see Fig. 4). The cross-coupling reaction was carried out with phenyl iodide and phenyl boronic acid in the presence of 0.1 mol % catalyst to better understand catalyst performance. The nano-catalyst was separated by filtration, washed with water, DCM, dioxane and reused. As depicted in figure 2, no significant loss in catalytic activity was observed after five cycles.

To better understand if the lost of activity was due to Pd leaching an ICP analysis of the catalyst after first usage was carried out and it was observed that catalyst loading remained constant.^{14d} Measured Pd weight % was 6.0% before usage and 5.95 after (Table 1, Entry 3). An XRD analysis which was carried out on a sample after catalysis only showed a slight increase in particle size, from 6.2 to 7.1 nm after usage (Figure 1, curve d).

To confirm that the reaction was catalyzed by Pd/Si-CD and not by the leached homogeneous Pd species, the model Suzuki reaction as well as the Heck reaction with iodo benzene and phenylboronic or styrene respectively were performed in two steps (see Supporting Information). The reaction was performed in oil bath and the hot reaction mixtures were filtered to remove

the Pd/SiCD. The reaction was monitored by GC-MS and only a slightly increased conversion was observed (1-5%), suggesting that all catalytic species were solid supported.²⁶

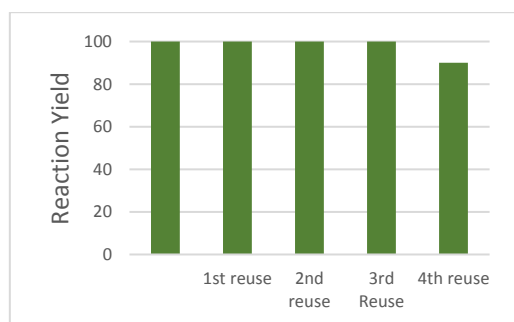


Figure 4. PdNPs/Si-CD catalyst reusability. Reaction conditions 1 eq. bromo benzene, 1.1 eq. boronic acid, 2 eq. TEA, 0.1% mol Pd (Pd/Si-CD), H₂O:Dioxane 9:1, 100°C, 30'

Finally, we explored the hydrogenation of a range of unsaturated hydrocarbons under 1 atm initial hydrogen pressure at r.t.. Pd/Si-CD (0.15 Pd mol %) showed excellent catalytic activity in the reduction of substrates with double and triple bonds to the corresponding alkane with excellent yields (>99%). The reduction of the azido and nitro groups furnished the corresponding amines in 2h. Benzaldehyde gave the corresponding alcohol in 1h at 50°C in a >99 % yield and the *p*-nitrobenzaldehyde was selectively reduced to *p*-amino benzaldehyde o.n. at r.t.

Table 7. Hydrogenation reaction ^[a]

En.	Starting Material	Final Product	Reaction condition	Yield
1			3h	>99
2			3h	>99
3			1h	>99
4			1h ^[b]	95
5			2h ^[c]	>99
6			o.n.	90

[a] reactions performed in hexane, 0.15% mol Pd, r.t., [b] The reaction was performed at 50°C, [c] the reaction was performed in methanol.

Conscious of the importance of alkyne semihydrogenation in providing the alkene derivative and of conventional monometallic Pd catalysts not giving high selectivity in these processes,²⁷ we proceed to evaluate the kinetics of the catalytic hydrogenation of phenyl acetylene. Five experiments were performed at room temperature under 1 atm initial hydrogen pressure and reactions underwent workup and analysis after 15, 30, 45, 60, 90, 120, 150 min. As depicted in Figure 5, full conversion of the alkyne was obtained in 60 min and the highest selectivity (alkene/alkane) achieved was >95%.

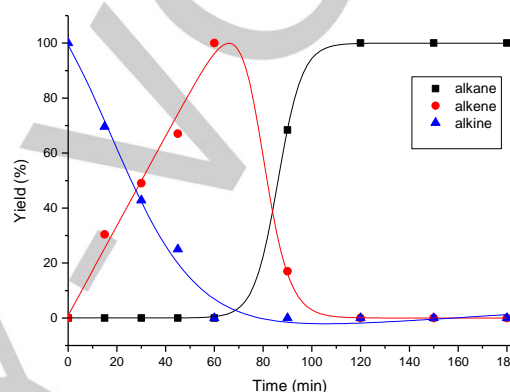


Figure 5. Percentage profile of the hydrogenation of phenyl acetylene with Pd/Si-CD ■▲●

Conclusions

In conclusion, we report the preparation of a new hybrid CD silica derivative supported PdNP catalyst. As the presence of a coordinating group is considered the key factor in the formation of small sized, homogeneously dispersed Pd nanoparticles, we herein demonstrate that CD grafted silica is an optimal support for this task. The amino alcohol groups and triazole on the spacer can also coordinate Pd species and influence PdNP content, size and distribution on the silica surface. An extensive study of the catalytic performances of this catalyst in ligand free C-C Suzuki and Heck couplings over a large number of aryl iodides and bromides has been reported. The catalyst exhibited excellent results and MW irradiation cut down reaction times. Pd/Si-CD showed high activity and selectivity in the hydrogenation reaction, while the semihydrogenation of phenylacetylene was studied giving excellent alkene/alkane selectivity. All protocols were designed to be ligand free and carried out without the addition of a stabilizer, in accordance with green chemistry criteria, while catalyst reuse was also evaluated. The Suzuki-Miyaura reaction was repeated five times and no significant loss in catalytic activity was observed. An ICP analysis of the catalyst after usage confirmed that catalyst amount was constant and XRD showed that NP diameter only increased slightly after usage.

Experimental Section

Materials and Method

All commercially available reagents and solvents were used without further purification. SIPERNAT 320 amorphous silica was supplied by Evonik Degussa. Reactions were carried out in professional MW reactor SynthWave (MLS GmbH, Milestone S.r.l. Mechanochemistry was performed in a planetary ball mill PM100 (Retsch GmbH). Si-G-U-CD was fully characterized as described in one of our previous studies. The cations were determined with a Perkin Elmer Optima 7000 (Perkin Elmer, Norwalk, Connecticut, USA) inductively coupled plasma-optical emission spectrometer (ICP-OES).

Preparation of Si-CD

(3-Glycidoxypropyl)methyldiethoxysilane (0.934 mL, 0.420 mol) was dissolved in toluene (10 mL) and silica SIPERNAT 320 (1 g) was added. The suspension was either heated under stirring in an oil bath (80 °C for 5 h) or in a MW reactor (80 °C for 1 h, average power 53 W). The modified silica was then filtered, washed thoroughly and dried under vacuum. Si-GPMS (1 g) and 10-undecynyl-1-amine (0.275 g, 1.64 mmol) were dissolved in DMF (3 mL). The solution was either heated to 80 °C and stirred for 24 h or the reaction was performed in a MW reactor (100 °C for 2 h, average power approximately 20 W). The silica was finally filtered and washed with DMF, water and toluene and dried under vacuum. Si-G-Und (1 g), 6-monoazido- β -CD (1.95 g, 1.68 mmol), $\text{CuSO}_4 \cdot 4\text{H}_2\text{O}$ (0.100 g, 0.4 mmol), and ascorbic acid (0.148 g, 0.84 mmol) were dissolved in H_2O (30 mL). The reaction was heated under MW at 80 °C for 2 h (average power approximately 12 W). Silica was filtered, washed with water and dried under high vacuum. The silica was purified of copper salts via the addition of $\text{Na}_2\text{H}_2\text{EDTA}$ (3.14 g), and dissolved in 5 mL H_2O . The suspension was left under magnetic stirring o.n.. The silica was then filtered, washed with water and dried under high vacuum.

Preparation of the Pd/Si-CD catalyst

$\text{Pd}(\text{OAc})_2$ (0.0024 g, 1.09 mmol) was dissolved in ethanol (5 mL) and Si-CD (0.250 g) was added. The suspension was heated under reflux and stirred in an oil bath for 2 h.

When the preparation of the catalyst was performed under US irradiation the reaction was sonicated (cup-horn, 90-100W, 20.4 kHz), for 1h and the temperature was maintained at 35-37 °C.

Characterization

Powder X-Ray Diffraction (XRD) patterns were measured on a PW3050/60 X'Pert PRO MPD diffractometer (Panalytical) working in Bragg-Brentano geometry using $\text{Cu K}\alpha$ radiation ($k = 1.5406 \text{ \AA}$) and operated at 45 kV, 40 mA with and step size of 0.0170° and time per step of 90 secs. Crystallite size $D = 4/3 L$ was calculated by applying the Scherrer's equation to the (111) peak at 39.33° :

$$L = k\lambda/(\beta\cos\theta)$$

where k is the X-ray wavelength, β the measured broadening of the diffraction peak and θ the diffraction angle. The measured β value was corrected by subtracting instrumental line broadening, estimated at 0.02° .

Transmission Electron Microscopy (HRTEM) measurements were performed on a JEM 3010-UHR microscope (JEOL Ltd.) operating at 300

kV. The sample powder was dispersed on a copper grid coated with a perforated carbon film for measurements.

Suzuki-Miyaura reaction

Aryl halide (0.5 mmol), boronic acid (0.55 mmol) and TEA (1 mmol) were dissolved in 5 mL of H_2O :Dioxane (9:1) and Pd/Si-CD (0.2mol % - 0.5mol %) were added. The reaction was carried out under magnetic stirring in a MW reactor SynthWave at 100 °C for 1 hour. The crude product was filtered on a Büchner funnel with a sintered glass disc using CH_2Cl_2 and Dioxane to wash the catalyst. After concentration to half volume under vacuum, the mixture was extracted with a HCl solution and CH_2Cl_2 , washed with H_2O three times and finally dried (Na_2SO_4). The crude product was analyzed by GC-MS and purified by flash chromatography on silica gel to afford the desired product. The pure product was analyzed using ^1H and ^{13}C NMR spectroscopy and MALDI-TOF mass spectrometry after dissolution in an appropriate solvent.

Heck reaction

The aryl halide (0.16 mmol), alkene or acrylate (0.2 mmol), K_2CO_3 (1 mmol) and Si-CD-PdNPs catalyst (1 mol%) were dissolved in a solution of H_2O : 1,4-Dioxane (1:1) or DMF (2 mL). The reaction was heated under MW at 120 °C for 30 min (average power approximately 25 W). The crude was filtered and washed with DCM. The desired product was extracted with DCM. The organic layer was washed three times with acid H_2O and finally dried (Na_2SO_4) and under high vacuum.

Hydrogenation reaction

The substrate (1 eq.) was dissolved in 3 mL of hexane (or MeOH) and Pd/Si-CD (0.156mol %) were added to the mixture. The reaction was carried out under magnetic stirring in an oil bath at r.t. or 50 °C for 1 to 2 hours. The solution was filtered through a $0.45 \mu\text{m}$ syringe filter and dried. The desired product was obtained without further purification.

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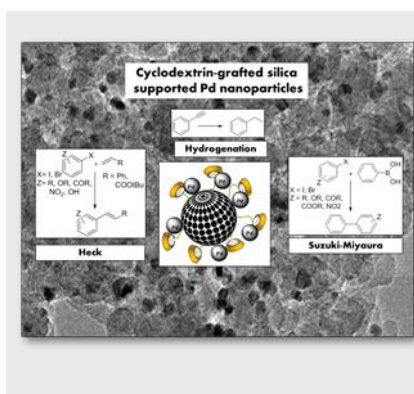
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