Green Chemistry

Cite this: DOI: 10.1039/c2gc16430b

www.rsc.org/greenchem

PAPER

Water mediated Heck and Ullmann couplings by supported palladium nanoparticles: importance of surface polarity of the carbon spheres†

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Received 9th November 2011, Accepted 24th May 2012
DOI: 10.1039/c2gc16430b

Heterogeneous palladium nanoparticle catalysts that are supported on amphiphilic carbon spheres (Pd@CSP) have been utilized for water-mediated Heck coupling reactions of aryl halides with different alkenes under phosphine free as well as aerobic conditions. Furthermore, a variety of Heck coupling reactions using different bases and solvents, including organic polar and non-polar solvents, have been explored. Aryl bromides are also well activated in Heck coupling reactions in organic polar solvent and as well as in water. In addition, Ullmann coupling reactions of aryl iodides have been catalyzed in water with the aid of phase transfer catalysts (PTC) in moderate yields. A plausible mechanism for the catalytic activity of Pd@CSP in the case of the Ullmann reaction is also established. It has been demonstrated that the hydrophobic effects of the catalyst surface play an important role in catalyst activity in water. In addition, the E-factor analysis verified that our present protocol is significantly comparable with other catalytic systems and explains the improved greenness. Moreover, the catalyst described in this process is not only greener, but also retains its significant activity for up to four catalytic cycles for the Heck coupling reactions. The surface polarity of the amphiphilic carbon spheres results in higher activity under these conditions.

Introduction

The Heck reaction was one of the first direct C–C coupling reactions to have a remarkably wide scope with the use of a palladium (Pd) catalyst, and is of particular interest in terms of sustainable chemistry.[1–7] This powerful reaction is widely used in industrial and academic applications, mainly for the coupling of aryl halides to electron-withdrawing terminal olefins.[6,8–19] Besides, the iodobenzene (Ar-I) homocoupling reaction (Ullmann reaction) has been extensively used for the synthesis of aromatic compounds for fine chemical, agrochemical, and pharmaceutical applications.[20,21] In the context of green chemistry, heterogeneous catalysis of the Ullmann reaction carried out in aqueous conditions is considered environmentally friendly since water could be considered as the safest solvent.[22–24] The use of water as the reaction media for the organic reactions is considerably greener compared to CO_2, ionic liquids and carefully selected traditional organic solvents in terms of the energy to manufacture, cumulative energy demand, and impact on health and the environment.[25] Indeed, the concepts of environmental factor (E-factor) and atom economy have gradually become included into conventional organic synthesis in both industry and academia. Solvents are the main reason for an insufficient E-factor, especially in fine chemicals and pharmaceutical industries.[26]

In view of the adverse environmental effects associated with phosphines, it is desirable to develop phosphine-free reactions under greener conditions for Pd-catalyzed reactions.[27–31] Besides, organic synthesis in water has drawn much attention as it is a non-toxic green solvent.[32–38] The use of water as a solvent particularly in the Heck reaction is important for E-factor reduction and for the development of safer industrial processes. One approach is to utilize water dispersible (hydrophilic) Pd catalysts.[7,39] Despite, the synthetic elegance and high turnover numbers, the non-reusability of the precious metal and the contamination of Pd in isolated products preclude wide synthetic applications in the pharmaceutical industry.

However, the coupling reactions of Heck substrates proceed sluggishly in pure water as the organic reagents are not completely dissolved in water.[40] Therefore, besides the usual problems associated with homogeneous catalysis (catalyst separation, product contamination, *etc.*), the conversion of the hydrophobic substrates is still a critical predicament for water dispersible catalysts. In order to circumvent these problems, a number of polymeric materials,[41–49] silica,[50] carbon,[51] silica carbon

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/c2gc16430b

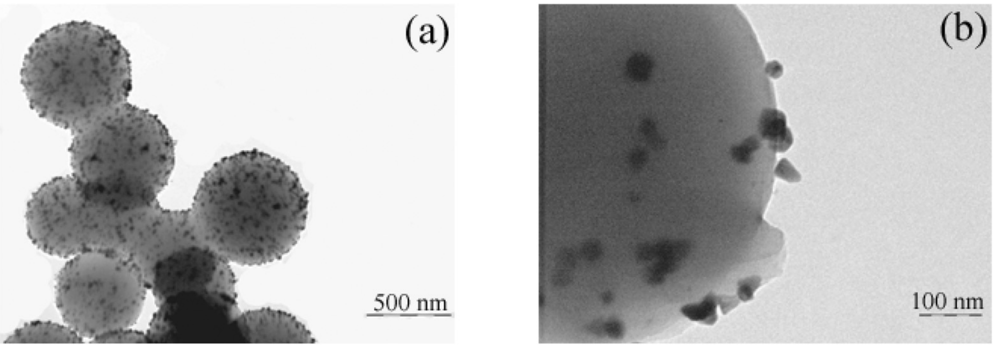


Fig. 1 TEM images of the Pd@CSP catalyst prior to the reaction (a) and after completion of the reaction (2nd cycle) (b).

composite,[52] have been developed and utilized as supports to perform the Heck coupling reactions in water. Besides, the "Breslow effect" has demonstrated that organic molecules repel water molecules and are forced to form clusters in order to decrease the surface area of the non-polar surface exposed to water. The hydrophobic aggregates arising from organic molecules in water will reduce the activation energies and increase the rate of the reaction significantly. In this context, we presumed that the water medium brings the organic molecules into close proximity of the carbon sphere (CSP) support by hydrophobic–hydrophobic interactions, which may influence the contact times of substrates with CSP support in the presence of phase transfer catalysts (PTC).[53] Hence, the amphiphilic property of the Pd@CSP may overcome the mass transfer limitation by increasing the availability of organic molecules near the CSP surface.

Various heterogeneous or supported Pd catalysts like Pd on carbon and a variety of metal oxides are shown to be highly active for Suzuki-coupling reactions in neat water under mild reaction conditions.[54] It is demonstrated that the surface polarity of the support plays an important role for the catalyst activity in water. Pd on amphiphilic carbon as a typical support represents a simple and green catalyst for the Suzuki–Miyaura reaction.[55] However, one of the substrates in the Suzuki reaction *i.e.*, phenyl boronic acid is easily soluble in water. Besides, both substrates in the Heck reaction are poorly soluble in water. It is worth mentioning that styrene and acrylates are also useful reactants in water, while they are poorly soluble in this solvent, similar to the aryl iodide counterpart. In order to extend the concept towards C–C coupling reactions catalyzed by Pd on an amphiphilic CSP catalyst in water, we have performed Heck and Ullmann coupling reactions in water under relatively mild reaction conditions (air, 90 °C, 0.5 mol% of Pd). Moreover, the catalytic activity was investigated by varying several parameters, such as solvent, base, and temperature. Among the solvents used, water is the best solvent system in comparison to other organic solvent systems in terms of catalyst activity, selectivity and stability. In addition, we have developed green reaction conditions *i.e.*, smaller E-factor (4.05), minimal usage of organic solvent, and a simple work up procedure. In addition, the greenness of the protocol is also improved by employing the applications of green chemistry metrics (E-factor). Furthermore, the comparison of E factor with several other catalyst systems explained the improved greenness of the present protocol.

However, the addition of tetrabutylammonium bromide (TBAB) to stabilize the dissolved Pd catalytic species and to diffuse the molecules onto the hydrophobic surface of the sphere in water was necessary for the conversion of various substrates to the corresponding products. The catalyst showed improved functional group tolerance to afford good-to-excellent yields of the products with different aryl halides. The majority of aryl halides afford good-to-excellent yields with higher amounts of *E*-diastereomers in pure water as well as in DMF. The recyclability of the CSP-supported Pd nanoparticles (Pd NPs) has also been demonstrated. Pd@CSP has been reused in water as well as in DMF for up to four cycles with excellent yields. On the other hand, few aryl iodides have been studied for Ullmann coupling reactions in pure water with the assistance of PTC under green (weak base, air and phosphine free conditions) reaction conditions, as it completely avoids the usage of such strong mineral bases (NaOH and KOH) as well as an external reducing agent (HCOONa and NaOMe).

Results and discussion

The TEM image in Fig. 1 shows that the synthesized Pd NPs on CSP are well distributed with an average size of 12 ± 0.5 nm and the size of CSP is typically 400–600 nm. CSP is readily dispersible in solvents of different polarity without any prior surface modifications due to its typical nature. This clearly demonstrates that the surface of CSP is polarized with hydrophobic and hydrophilic functionalities as shown in Fig. 2. TGA analysis showed that the negligible decrease in catalyst weight at 100–120 °C may be attributed to the loss of sorbed water molecules by evaporation (ESI†). Temperature programmed desorption of ammonia (NH_3-TPD) shows that the broad ammonia desorption profile in the range of 280–600 °C is observed. The broad peak is an indication of the presence of –COOH functional groups (ESI†). XPS analysis of the Pd@CSP catalyst indicated that it exclusively contains Pd(0). The catalytic activity of Pd@CSP was examined for various Heck and Ullmann coupling reactions under phosphine free and aerobic conditions.

The initial screening of the reaction was carried out not only on the basis of high yield, but also by considering the green reaction conditions (lower E-factor; Table 1, ESI†). The eco-friendly Heck coupling reaction between iodobenzene and styrene in water with the aid of PTC (TBAB) afforded 90% yield of the

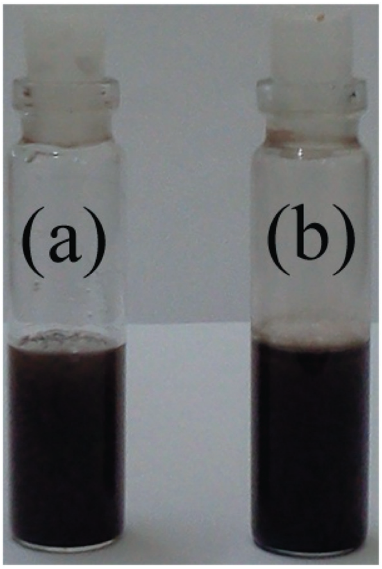


Fig. 2 Sonicated solution of Pd@CSP in toluene (a) and water (b).

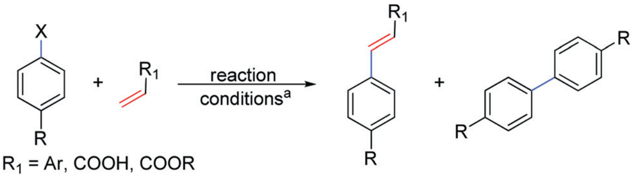
product with 100% selectivity in 7 h (Table 1, entry 1). We then examined this coupling reaction with a variety of aryl halides and different alkenes, in which a reaction between aryl iodide and acrylic acid proceeded smoothly within 1.5 h (Table 1, entry 10). Addition of PTC to the reaction mixture not only initiated the diffusion of molecules on to the hydrophobic surface of the sphere in water, but also stabilized the leached Pd active species. The products were separated by simple organic extraction and purified *via* crystallization. The yields obtained depended on the "surface polarity" of both the support and water. Analysis of the filtrate from the two consecutive reactions shows that the amount of Pd lost in solution is of the order of parts per million (0.4 ppm of Pd) as determined by AAS analysis. The recovered catalyst was used in four further runs for the arylation of methyl acrylate with iodobenzene and showed a slowly decreasing activity upon further reuse, as shown in Fig. 3. After each run, the supported catalyst was recovered by simple filtration and reused directly for the next run of the reaction without further manipulation. A plot of the kinetic analysis for the catalytic activity of Pd@CSP is illustrated in Fig. 4, for the Heck coupling reaction of iodobenzene and methylacrylate in H_2O. The catalyst was reused at the fourth cycle without any marked loss in the activity. Further, the kinetic data for the "homeopathic catalysis" (0.05 mol%) was carried out under the same reaction conditions (ESI†). XPS analysis of the Pd@CSP catalyst after the reaction revealed that the oxidation of Pd(0) to Pd(II) was not significant under the reaction conditions (Fig. 5).

A variety of aryl iodides react with various alkenes, including acrylic acid, acrylates, styrene, and its derivatives, to give the required products in water with good to excellent yields (~62–95%) (Table 1). Interestingly, the ability of the Pd@CSP to promote the coupling reaction of acrylic acid and different acrylates with a variety of aryl halides, including activated and non-activated aryl bromides is satisfactory, but not excellent in the case of chlorides (Table 1). Moreover, aryl bromides are activated in DMF in the case of all types of counterparts (styrene, acrylic acid, and acrylates) and delivered good yields (Table 2). Despite extensive experimentation, all attempts include the aryl bromides as electrophiles in the case of styrene in water have failed. In addition, the reaction takes place selectively at the iodo functionality of aryl halides as in case of 1-chloro-4-iodobenzene (Table 1, entry 5), wherein complete chemoselectivity is achieved for the Heck reaction. The reactions of aryl halides with styrene at 50 °C are unsatisfactory and the yields are relatively low, 25% (Table 1, entry 1). The catalyst showed improved functional group tolerance to afford good to excellent yields of the products with different aryl iodides. Some of the heterocyclic halides also reacted smoothly and obtained good yields for the Heck coupling reaction in water as well as in DMF (Table 1, entries 8, 9 and Table 2, entries 3, 4). Among the bases used, K_2CO_3, Na_2CO_3, Et_3N, TBA, IPA, NaOH and NaOAc, all gave excellent yields except NaOH and NaOAc, as shown in Table 3. It was observed that Pd NPs precipitated out of the solution when a strong base was used.[56] It is proposed that the dissolution of the Pd species from the surface of the solid-support or the Pd clusters leads to the formation of the active species in the solution, and Pd is redeposited on the support or on the Pd clusters as the reaction system cools down.[57,58]

Then, we carried out the coupling reaction of iodobenzene with styrene in DMF. It was found that DMF in combination with Et_3N as the base gives 98% isolated yield (Table 2, entry 1) in 1 h. A variety of aryl iodides, aryl bromides and aryl chlorides react with various styrene, acrylic acid, acrylate, and its derivatives to give the required products with moderate to excellent yields (30–98%, Table 2). These good yields were attributed to the hydrophobic interactions among the precursors used and proves the importance of surface polarity of the carbon spheres towards usage of solvents with different polarities. A combination of DMF–H_2O (9 : 1) solvent system was employed, providing improved yields and selectivities for activated aryl bromides. The fact that leached Pd is active in the aqueous co-solvent compared to organic solvents alone might be due to traces of water which stabilizes Pd(II) in solutions. Hence, the water was used not only to solubilize the base, but also to enhance the catalytic activity. Among the bases used, K_2CO_3, Na_2CO_3, Et_3N, TBA, IPA, NaOH and sodium acetate gave excellent yields except NaOH and NaOAc in DMF, as depicted in Table 3. When the catalyst loading was reduced to 0.05 mol%, the time taken to complete the reaction was 8 h (Table 2, entry 1). Furthermore, we also investigated the recycling of the supported Pd on a model reaction of iodobenzene with styrene (Table 2, entry 1). The catalyst exhibited a marginal loss in activity and required a slightly longer reaction time to achieve similar results after the second cycle. All aryl iodides afford good to excellent yields with more *E*-diastereomer in pure water as well as in DMF.

To examine the leaching of Pd from the solid catalyst, a hot filtration test was performed both in pure water as well as DMF individually for the reaction of iodobenzene with styrene to yield ~70% of the coupling product, wherein it took 24 h for this process. The leaching of the Pd from the CSP support was demonstrated by performing a reaction under the typical conditions, by filtering the solid after 3 h, while the mixture was still hot. Atomic absorption spectroscopy (AAS analysis) showed that ~3.4 ppm of Pd was found in the filtrate. No residual Pd was observed in the final products as determined by AAS. The

Table 1 The Heck coupling reaction of different aryl halides with different alkenes over Pd@CSP in water[a]



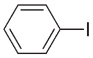
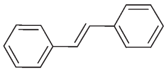
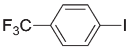
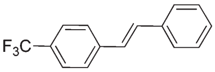
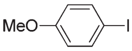
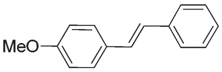
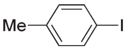
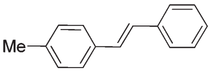
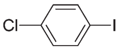
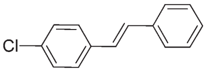
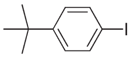
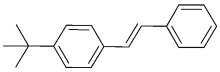
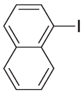
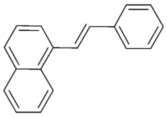
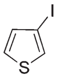
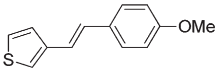
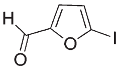
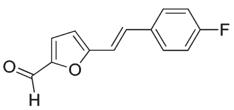
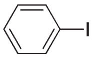
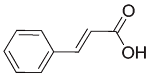
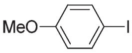
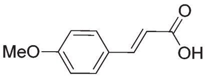
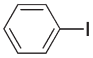
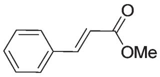
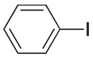
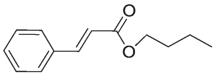
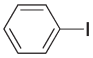
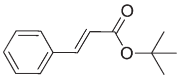
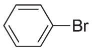
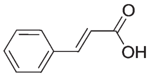
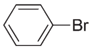
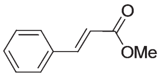
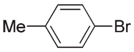
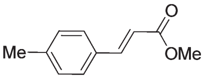
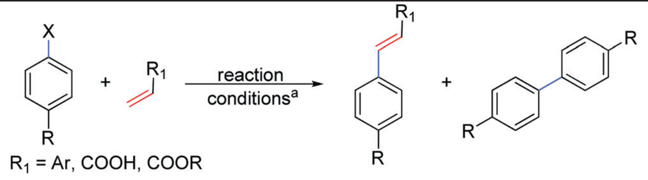
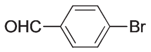
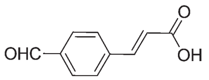
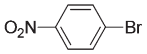
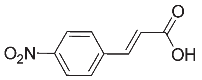
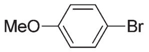
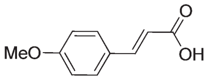
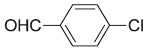
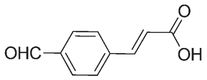
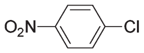
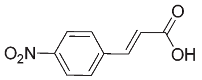
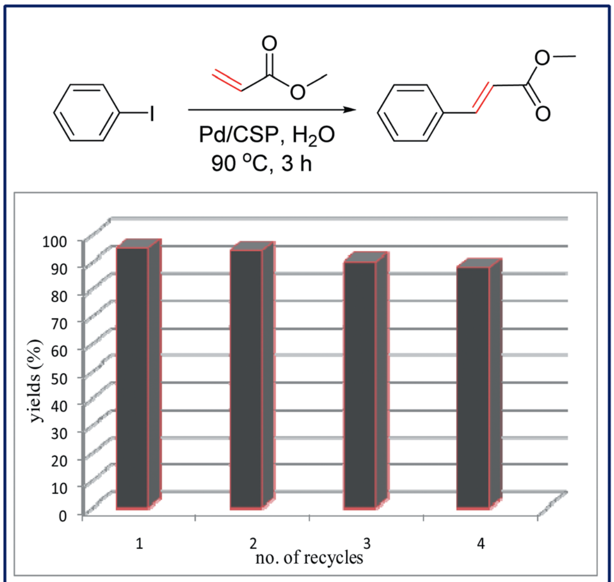
Entry	Aryl halide	Product	Yield[b] (%)	Time (h)	Selectivity[c] (Heck product/biphenyl)
1			90, 25,[d] 55,[d] 25[e]	7.0, 30,[d] 3 d,[d] 6.5[e]	100 : 0, 80 : 20,[d] 52 : 48,[d] 85 : 15[e]
2			87	6.5	100 : 0
3			80	10	98 : 2
4			82	9.0	96 : 4
5			86	9.0	95 : 5
6			82	10	92 : 8
7			90	11	100 : 0
8			62	12	93 : 7
9			68	12	95 : 5
10			90	1.5	100 : 0
11			88	2.5	100 : 0
12			95	3.0	100 : 0
13			91	3.0	98 : 2
14			92	3.0	95 : 5
15			70	10.0	98 : 2
16			65	11.0	95 : 5
17			57	12.0	90 : 10

Table 1 *(Contd.)*



Entry	Aryl halide	Product	Yield[b] (%)	Time (h)	Selectivity[c] (Heck product/biphenyl)
18			76	10.0	100 : 0
19			75	9.0	100 : 0
20			50	15.0	90 : 10
21			25	24.0	—
22			30	21.5	—

[a] Reaction conditions: aryl iodide (0.32 mmol), alkene (0.416 mmol), TEA (0.48 mmol), TBAB (0.32 mmol), Pd@CSP (5 mg, 0.5 mol% *vs.* halide) and 4 mL of H_2O. [b] Isolated yields. [c] Selectivity of Heck product determined by ^{1}H NMR. [d] Reaction conducted at 50 °C. [e] Reaction performed in toluene.



ᵃReaction conditions: iodobenzene (0.32 mmol), methyl acrylate (0.416 mmol), TEA (0.48 mmol), TBAB (0.32 mmol), Pd/CSP (5 mg, 0.5 mol% vs halide), water (4 mL), 90 °C, air, 3 h. ᵇIsolated yields.

Fig. 3 Recycling experiments for the Heck coupling of methyl acrylate and iodobenzene by Pd@CSP in water.

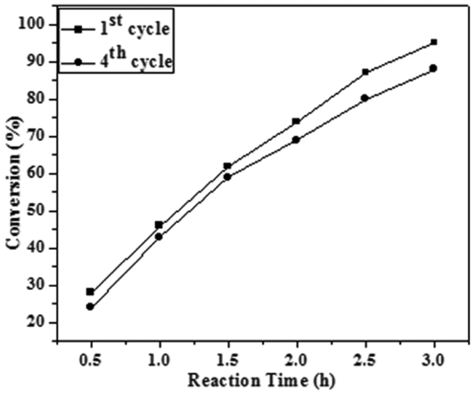


Fig. 4 Analysis of conversion *vs.* reaction time for the catalytic activity of Pd@CSP for the Heck coupling reaction of iodobenzene and methylacrylate in H_2O. The conversion was monitored by GC.

performance of the reaction in toluene thus showed the importance of leaching for better conversion.[59] It is assumed that the support firmly binds to the Pd(II) species and prevents it from aggregation during the course of the reaction. The TEM image of the catalyst after the third cycle showed a small agglomeration of nanoparticles. It was observed that the catalyst is very active due to the surface polarity of the support for the Heck reaction and can be recovered and reused for upto four cycles. The slower solubilization of the support is observed over extended recycling, however solubilization is much faster in DMF than in water. The solubilization of the catalyst system in organic solvents may be due to greater penetration of solvent molecules to the hydrophobic surface under heating conditions. These heterogeneous catalysts showed good stability for various coupling reactions in pure water.

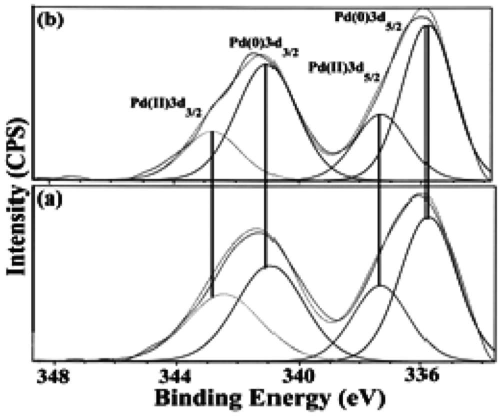


Fig. 5 XPS narrow scan for Pd (a) in fresh Pd@CSP and (b) in used (after 2nd cycle) Pd@CSP for the Heck coupling of methyl acrylate and iodobenzene in water.

Conventionally, external reducing agents are needed in the Ullmann coupling reactions. Under these conditions, only two products are identified during the Ar–I Ullmann coupling reaction over different Pd-based supported catalysts. One is the target product biphenyl (Ar–Ar) which results from the coupling reaction of Ar–I. The other is the side-product benzene which results from dehalogenation of Ar–I to Ar–H. The external reducing agents such as HCOONa or NaOMe are used to reduce Pd(II) for regenerating the catalyst, and the base (*e.g.* KOH or NaOH) is used to neutralize the HX resulting from the reduction of PdX_2.[24] For the various iodobenzenes Ullmann coupling reaction in aqueous conditions, Pd@CSP exhibited good activity and complete selectivity due to the surface polarity of the CSP toward the desired product (biphenyl) under mild reaction conditions such as a mild base (K_2CO_3) and without a reducing agent (HCOONa) (Table 4). The functional groups present on the CSP might be acting as relatively weak *in situ* reducing agents for PdI_2.[60] However, the catalyst support could not be collected for further analysis, due to the solubilization of the support over extended reaction time. The use of NaOH as the base instead of K_2CO_3 led to the formation of ~10% of phenol, followed by the complete quenching of the reaction due to the lower stability of Pd NPs in the increased ionic strength of NaOH solution resulting in ineffective protection of CSP to Pd NPs. The surface polarity of the CSP led to improved efficiency of this catalyst system in terms of activity, and reusability has been observed compared to other polymeric support systems.[41a,43,50,61] In addition, we have calculated and compared the E-factor value with several supported Pd NPs catalyzed Heck coupling reactions, which are performed in water. We excluded water from the E-factor calculations as its inclusion would lead to extremely high E-factors in many cases and make any meaningful comparison of processes difficult.[26] The result shows that our present protocol is compares favourably with other processes and explains the improved greenness (Table 2, ESI†).

Conclusions

In conclusion, we have explored an efficient heterogeneous catalyst system for the water mediated Heck and Ullmann coupling reactions of aryl halides using amphiphilic CSP supported Pd NPs. Various Heck coupling reactions utilising different bases and solvents including organic polar and non-polar solvents have been studied. Moreover, it was demonstrated that water is the best solvent in comparison to other organic solvent systems in terms of catalyst activity, selectivity and stability. Furthermore, the catalysts were reused for Heck coupling reactions in water as well as in DMF. However, the catalysts could not be reused for the Ullmann coupling reactions probably due to the extensive reaction times, which led to the solubilization of most of the catalyst support in water. The carboxylate functionalities present on the carbon spheres are effective for preventing the aggregation of the leached active Pd species during the reaction. Using amphiphilic CSP supported Pd catalysts in Heck and Ullmann coupling reactions in water, it has been verified that the effect of surface polarity of the CSPs has a pronounced influence on the catalyst activity. In fact, optimization of the E-factor for the Heck coupling reaction confirmed that the use of water as the solvent is efficient for waste reduction. It is interesting to observe that the E-factor is 4.05 and it is significantly smaller than some other protocols reported in the literature. The better performance of Pd@CSP catalyst in water is attributed to the amphiphilic property of the CSP support and the "Breslow effect". This catalytic method is an efficient green process for C–C bond formation reactions which includes merits such as high yields and cost effectiveness.

Experimental

Synthesis of colloidal carbon spheres (CSP)

The procedure for preparing carbon spheres was in accordance with the reported method by Sun and co-workers.[62] Glucose (4 g) was dissolved in distilled water (40 mL) by stirring for 0.5 h, and then the solution was placed in a 40 mL Teflon-sealed autoclave and maintained at 180 °C for 6–8 h. The final product was isolated by centrifugation, cleaned by three cycles of centrifugation/washing/redispersion in water and in ethanol, and oven dried at 60 °C for 8 h.

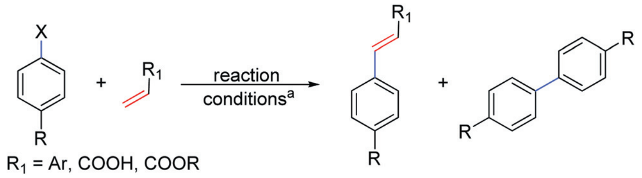
Synthesis of CSP supported Pd nanoparticle catalysts

The synthesis of the CSP supported Pd NPs is reported in the literature.[63] Briefly, carbon spheres (50 mg) were dispersed in absolute EtOH (25 mL) by sonicating for 30 min. Then, $PdCl_2$ (13 mg) was added into the above suspension, followed by reacting at 70 °C for 1 h under vigorous stirring. After, the reaction mixture was centrifuged, washed twice with distilled water, and dried at 60 °C for 12 h. AAS analyses showed that 3.8 wt% of Pd was found in the CSP supported Pd nanoparticle catalyst.

Typical reaction procedure for the Heck reaction in H_2O

The Pd catalyst (5 mg, 0.5 mol% of Pd@CSP) was added to the reaction vessel with 4 mL of H_2O, sonicated for 5 min. Then, the aryl halide (0.32 mmol), vinylating agent (0.416 mmol), TEA (0.48 mmol), and TBAB (0.32 mmol) were mixed in catalyst suspension. The reaction mixture was heated to 90 °C and

Table 2 The Heck coupling reaction of different aryl halides with different alkenes over Pd@CSP in DMF[a]



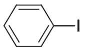
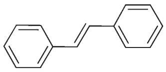
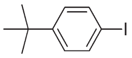
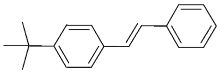
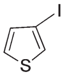
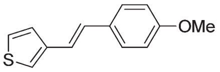
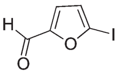
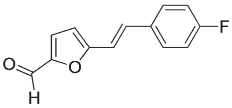
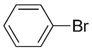
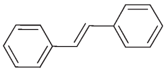
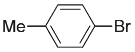
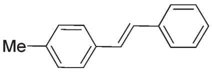
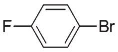
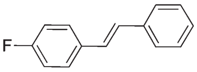
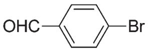
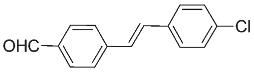
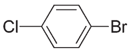
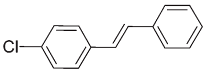
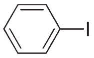
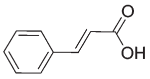
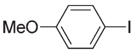
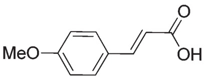
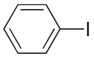
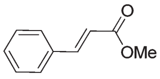
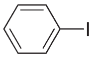
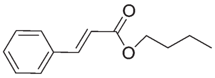
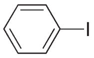
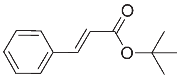
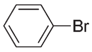
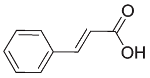
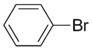
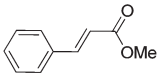
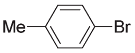
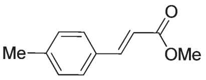
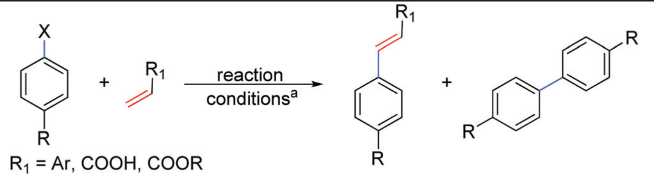
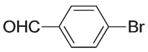
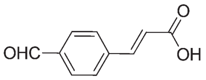
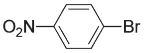
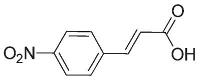
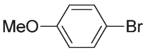
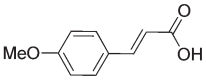
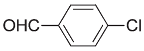
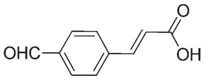
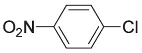
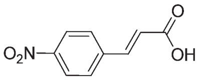
Entry	Aryl halide	Product	Yield[b] (%)	Time (h)	Selectivity[c] (Heck product/biphenyl)
1			98, 90[d], 80[e]	1.0, 8.0[d], 2.0[e]	100 : 0, 100 : 0[d], 95 : 5[e]
2			97	2.0	95 : 5
3			75	8.0	90 : 10
4			80	7.0	92 : 8
5			85	6.0	79 : 21
6			80	7.0	75 : 25
7			80	8.0	78 : 22
8			82	6.0	75 : 25
9			75	8.0	85 : 15
10			93	1.0	100 : 0
11			96	2.0	100 : 0
12			95	1.0	100 : 0
13			96	1.5	98 : 2
14			95	1.5	94 : 6
15			82	4.0	85 : 15
16			90	6.0	85 : 15
17			62	7.0	78 : 22

Table 2 *(Contd.)*



Entry	Aryl halide	Product	Yield^b (%)	Time (h)	Selectivity^c (Heck product/biphenyl)
18			89	5.0	90 : 10
19			91	5.0	90 : 10
20			63	10.0	78 : 22
21			30	22.0	—
22			32	20.0	—

[a] Reaction conditions: aryl halide (0.32 mmol), alkene (0.416 mmol), TEA (0.64 mmol), Pd@CSP (5 mg, 0.5 mol% *vs.* halide) and 4 mL of DMF. [b] Isolated yields. [c] Selectivity of Heck product determined by ^{1}H NMR. [d] 0.05 mol% of Pd@CSP was used. [e] Isolated yield and time at 3rd cycle.

Table 3 Screening of several bases in different solvents for Heck coupling of iodobenzene with styrene

Entry	Base	Yield^a (%)		Time (h)		Selectivity	
		$H_2O^{b,c}$	$DMF^{b,d}$	$H_2O^{b,c}$	$DMF^{b,d}$	$H_2O^{b,c}$	$DMF^{b,d}$
1	TEA	90	98	7.0	1.0	100 : 0	100 : 0
2	TBA	88	96	7.0	1.0	95 : 5	98 : 2
3	IPA	84	90	7.5	1.5	95 : 5	98 : 2
4	K_2CO_3	83	90	6.5	1.5	93 : 7	93 : 7
5	Na_2CO_3	85	92	6.5	1.5	93 : 7	93 : 7
6	NaOAc	7	5	8.0	7.0	—	—
7	K_3PO_4	75	72	7.5	2.0	94 : 6	96 : 4
8	NaOH	10	—	7.5	—	—	—

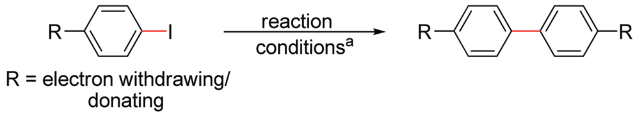
[a] Isolated yields. [b] Reaction conditions: Pd@CSP (5 mg, 0.5 mol% *vs.* halide) and 4 mL of H_2O or DMF, under air, heated at 90 °C for H_2O or DMF respectively. [c] Aryl halide (0.32 mmol), alkene (0.416 mmol), TEA (0.48 mmol), TBAB (0.32 mmol). [d] Aryl halide (0.32 mmol), alkene (0.416 mmol), TEA (0.64 mmol).

the progress of reaction was monitored by TLC. After completion of the reaction, the reaction mixture was allowed to cool at 0 °C for 1 h. For isolation of the solid products, first the reaction mixture was filtered by rinsing with cold water (3 × 5 mL) to remove the excess TEA, TBAB and salts formed during the course of reaction. In the next step, the catalyst was separated out by filtration and thoroughly washed with cold ethanol (3 mL). However for isolation of the liquid products (Table 1, entries 12, 13, 14, 16, and 17), the catalyst was first separated out by filtration and thoroughly washed with water followed by hexane (4 mL). Then, the collected organic portions in both cases were dried over anhydrous Na_2SO_4, concentrated under reduced pressure and the residue was purified by flash chromatography using 250–400 mesh silica and hexane alone or a mixture of ethyl acetate and hexane as eluent. The organic solvents used for the purification were recycled under reduced pressure and reused successfully. Isolated yields and purity of the product were confirmed by ^{1}H NMR.

Typical reaction procedure for the Heck reaction in polar organic solvent

The Pd catalyst (5 mg, 0.5 mol% of Pd@CSP) was added to the reaction vessel with 4 mL of DMF and sonicated for 5 min. Then, the aryl halide (0.32 mmol), vinylating agent

Table 4 Ullmann coupling reactions of aryl iodides over Pd@CSP in water[a]



Entry	R group	Time (h)	Yield[b] (%)
1	H	22	52
2	*p*-NO_2	20	55
3	*p*-CHO	20	53
4	*p*-Me	24	50
5	*p*-Cl	21	44
6	*p*-OMe	23	48

[a] Reaction conditions: aryl iodide (0.32 mmol), K_2CO_3 (0.64 mmol), TBAB (0.64 mmol), water (4 mL), Pd@CSP (5 mg, 0.5 mol% Pd *vs.* halide), heated at 90 °C, under air. [b] Isolated yield.

(0.416 mmol), and TEA (0.64 mmol) were mixed in catalyst suspension. The reaction mixture was heated to 90 °C and the progress of reaction was monitored by TLC. After the completion of the reaction, mixture was cooled to room temperature and filtered over Teflon membrane (PTFE, 0.2 μm pore size) filter paper. Then, 20 mL of ethyl acetate was added to the filtrate, and washed with crushed ice three times. The organic phase was dried over anhydrous Na_2SO_4, and evaporated under reduced pressure. The residue was purified by column chromatography using ethyl acetate and hexane as a mobile phase to afford the heck product in high purity. The organic solvents used for the extraction and purification were recycled under reduced pressure and reused successfully. Isolated yields and purity of the product were confirmed by ^{1}H NMR.

Reusability study of the catalyst

After completion of the reaction, the waste medium was cooled to room temperature and the catalyst was recovered by filtration over a Teflon membrane (PTFE, 0.2 μm pore size) and used for the next catalysis cycle after sufficient washing with CH_2Cl_2 and water (necessary to remove salts in the form of excess base) followed by acetone and subsequent drying.

Typical reaction procedure for the Ullmann coupling reaction

The Pd catalyst (5 mg, 0.5 mol% of Pd@CSP) was added to the reaction vessel with 4 mL of H_2O, sonicated for 5 min. Then, the aryl halide (0.32 mmol), K_2CO_3 (0.64 mmol), and TBAB (0.64 mmol) were mixed in catalyst suspension. The reaction mixture was stirred at 90 °C under air and the progress of reaction was monitored by TLC. After completion of the reaction, the reaction mixture was allowed to cool at 0 °C for 1 h. Then, the reaction mixture was filtered by rinsing with cold water (3 × 5 mL) to remove the excess K_2CO_3, TBAB and salts formed during the course of reaction. In the next step, the catalyst was separated out by filtration and thoroughly washed with cold ethanol (3 mL). Then, the collected ethanol was dried over anhydrous Na_2SO_4, concentrated under reduced pressure and the residue was purified by flash chromatography by using 250–400 mesh silica and hexane alone or a mixture of ethyl acetate and hexane as eluent. The organic solvents used for the purification was recycled under reduced pressure and reused successfully. Isolated yields and purity of the product were confirmed by ^{1}H NMR.

Acknowledgements

V.S., B.N.S., and N.M.K., are thankful to CSIR, New Delhi, for the award of research fellowships.

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