



Tetrahedron report number 804

Silica-supported Pd catalysts for Heck coupling reactions

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Received 27 March 2007

Available online 13 April 2007

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Keywords: Heck reaction; Palladium catalyst; Silica; Ionic liquid; Pd-leaching.

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1. Introduction

Improving the efficiency of organic processes in terms of conservation of energy, lowering the process time and inventory of equipment and minimising the use of chemicals and production of waste is a major goal in synthetic chemistry. The efficient separation and subsequent recycling of homogeneous transition-metal catalysts remains a topic that not only constitutes scientific challenges, but also is of commercial relevance. The practical use of the ever-increasing number of tailor-made transition-metal catalysts¹ is indeed limited by the cumbersome separation from the product phase, especially for application in the fine-chemical industry.^{2,3} For bulk chemicals, several simple unit operations are applied, such as distillation, extraction, filtration and two-phase catalysis.⁴ So far, several strategies for advanced catalyst recycling have been explored, including supported aqueous-phase catalysis,^{5–7} fluorosoluble-phase catalysis^{8–14} and the use of ionic liquids^{15–20} and supercritical fluids.^{21–23} The heterogenisation of homogeneous catalysts and their use in fine chemical synthesis has become a major area of research, since the potential advantages of these materials over homogeneous systems can have positive environmental consequences.^{24,25}

The Heck reaction is among the most important and widely used reaction for the formation of carbon–carbon bonds, which allows the arylation, alkylation or vinylation of various alkenes through their reaction with aryl, vinyl, benzyl or allyl halides, acetates or triflates in the presence of palladium and a suitable base in a single step under mild conditions.^{26–33} A Heck-type reaction was first described^{34a} by Mizoroki et al. before Heck published his first results.^{34b} Attractive features are the versatile application possibilities and the tolerance of the reaction for a wide range of functional groups. There are examples for the realisation of the method on an industrial scale in fine chemical synthesis.^{35,36} The reaction is appealing because of its tolerance for nearly any solvent and functional group on the substrates, its high selectivity and its moderate toxicity.^{37,38} Academic and industrial interest in this reaction has increased in recent years, including the advent of an enantioselective variant,^{39,40} the development of more active catalyst systems, the discovery of waste-free versions^{41,42} and the desire to put the vast empirical data on a sound mechanistic basis.^{43,44}

In recent years, however, most studies have focused on the use of soluble Pd complexes with various types of ligands^{26,27} with the aim of increasing the effectiveness of the catalysts. The driving force of these efforts is to develop Pd complexes with new ligands of high activity and to find appropriate reaction conditions for the conversion of non-activated bromoarenes and the more readily available, but least reactive, chloroarenes.^{45–59} It was also shown that ionic liquids greatly advance the Heck reaction and allow the recycling and re-use of the catalysts.^{60–65}

Homogeneous catalysts, however, suffer from the problems associated with the need and handling of sensitive ligands, and the difficulty of catalyst recovery, recycling of the expensive Pd, separation and deactivation via the aggregation of Pd nanoparticles formed in situ during the Heck reaction. To overcome these problems, it is highly desirable to develop heterogeneous catalysts for industrial applications. Successful methods include supporting Pd complexes on polymers,^{66–69} anchoring Pd complexes to various solids such as modified silicas^{70–72} or layered double hydroxides⁷³ and ion exchange of Pd²⁺ into suitable solid materials.^{74–79} Furthermore, there has been a search for suitable supported heterogeneous Pd catalysts and in fact, heterogeneous Pd catalyst systems were found to be highly effective. In addition, in order to stabilise colloidal palladium and palladium nanoparticles,^{80–88} numerous reports have shown the utility of various supported palladium catalysts.⁸⁹ Commercial Pd on active carbon was studied most,^{90–95} along with Pd supported on mesoporous MCM-41,^{96,97} molecular sieves,^{98–101} oxides,¹⁰² layered double hydroxides¹⁰³ and Pd(OH)₂/C.¹⁰⁴ Efforts have also been made to extend the scope of the heterogeneous Heck reaction to the least reactive chloroarenes. In fact, recent results show that the Heck coupling of chloroarenes can be induced by Pd on carbon,⁹⁵ Pd nanoparticles deposited on layered double hydroxides¹⁰³ or by solid Pd catalysts having highly dispersed Pd²⁺ species¹⁰⁵ to give the corresponding vinyl arenes in high yields under appropriate reaction conditions.

The majority of the novel heterogenised catalysts are based on silica supports,^{106,107} primarily because silica displays some advantageous properties, such as excellent stability (chemical and thermal), good accessibility and the fact that organic groups can be robustly anchored to the surface to provide catalytic centres. Ordered mesoporous silica materials prepared by micelle-templated synthesis^{108–113} have recently found wide application as catalyst materials. Among the various possibilities, surface modification has been used quite extensively to produce active catalytic materials. The functional groups of such hybrid organic–inorganic materials¹¹⁴ may serve as anchoring sites for metal complexes (heterogenisation of homogeneous catalysts) or, having suitable catalytic properties, they may act as surface active sites.^{115–117} Metallic palladium has been incorporated into various silica materials including amorphous silica^{118,119} and ordered mesoporous silicas such as MCM-41,¹²⁰ HMS,¹⁰⁶ SAB-15¹⁰⁶ and ETS-10.¹⁰¹ These heterogeneous systems have been effectively used as catalysts in hydrogenation and in Heck coupling reactions.

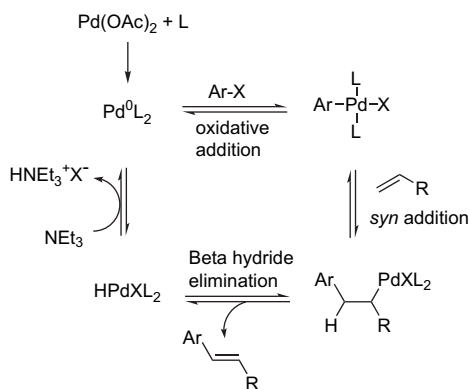
The clearly increasing number of papers concerning the heterogeneously catalysed Heck reaction reflects the efforts to solve the problems discussed above and also to understand the mechanism of this reaction. Recent reports focus on, or at least describe, investigations of the leaching phenomenon, which is important to realise the actual active species and to

manage the complete separation of Pd. Some papers deal with the influence of the structure of the Pd surface (structure–activity relationships), while others question whether the heterogeneous reaction is catalysed homogeneously or heterogeneously. This review focuses on all of the above aspects with respect to the use of silica-Pd catalysts in Heck coupling reactions.

2. Mechanism of Heck reaction

2.1. Pd⁰ to Pd^{II} mechanism

The standard catalytic cycle described for the Heck reaction in most organic chemistry textbooks involves a postulated molecular, homogeneous palladium catalyst that cycles between the Pd⁰ and Pd^{II} oxidation states during the course of the catalytic reaction.¹²¹ The catalyst is generated from e.g., Pd(OAc)₂ and ligand L [PPh₃ or P(*o*-MeC₆H₄)₃], which gives Pd⁰L₂. PdL₂ then reacts with ArX to give ArXPdL₂, which subsequently loses another L and complexes to CH₂=CHR. After addition of Ar–Pd across C=C and β-hydrogen elimination, ArCH=CHR and NEt₃H⁺X⁻ are produced and Pd⁰L₂ is regenerated (Scheme 1).



Scheme 1. Pd⁰ to Pd^{II} mechanism of Heck reaction.

2.2. Silica-supported mechanism and palladium redeposition

The mechanism of the Heck vinylation of iodobenzene with supported palladium catalysts in an NMP (*N*-methylpyrrolidone) solvent with Et₃N and Na₂CO₃ as bases was proposed as shown in Scheme 2.⁹² In the first step, soluble palladium complexes are formed by the coordination with the polar solvent NMP and/or organic base Et₃N, and these are the catalytically active species. When iodobenzene is present, its oxidative addition to these palladium complexes occurs and the reaction continues to go homogeneously in the solvent, according to the accepted mechanism of the Heck reaction. When iodobenzene is completely consumed and is absent in the reaction mixture, however, the complexes are not so stable that the palladium will go back on to the surface of the support (redeposition). In the last step of reductive elimination, mainly Na₂CO₃ acts, rather than Et₃N.

Since not all palladium species leach out into the solvent, the dissolved palladium could redeposit on two possible sites, which are the bare surface of the support and the surface

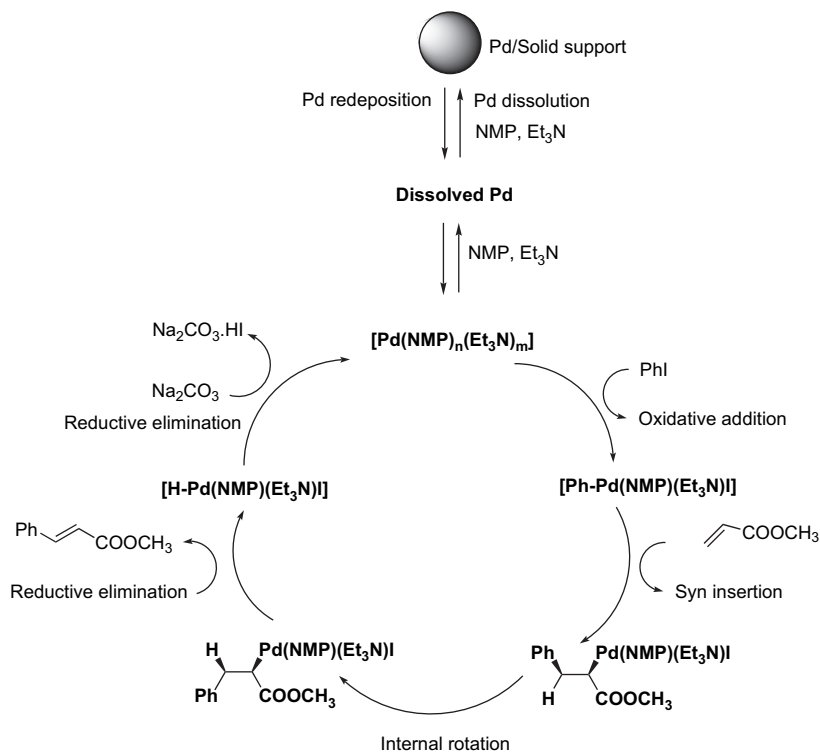
of the palladium particles remaining on the support. The redeposition occurs preferentially on the surface of the residual palladium particles, rather than on the bare surface of the support. Other factors, such as the nature of the surface of the support and/or the number and size of the residual metal particles may, however, affect the redeposition process. Furthermore, it was also found that the surface functional groups on carbon and silica may also significantly influence palladium re-deposition.

2.3. Pd^{II} to Pd^{IV} mechanism

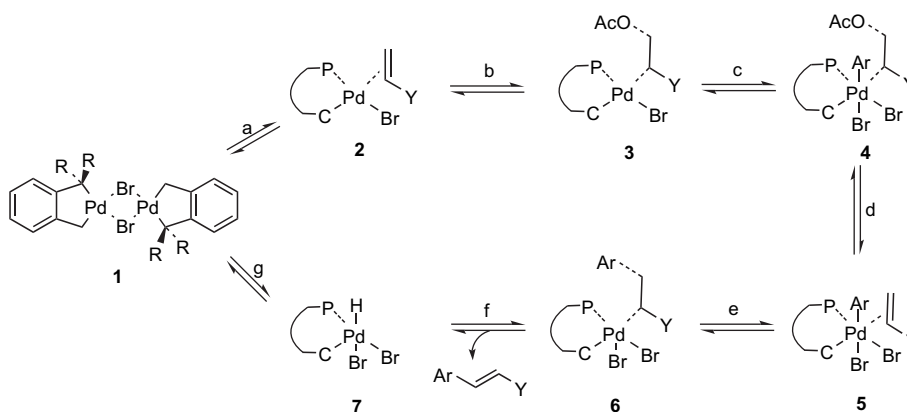
Shaw^{122,123} proposed a new mechanism for the Heck reaction (Scheme 3). The new features are that the Pd^{II} metallacycle such as **1** is coordinated by the olefin (**2**), which then undergoes nucleophilic attack to give a σ-alkyl complex (**3**). The resultant electron-rich Pd^{II} complex then undergoes oxidative addition with an aryl bromide, or an other organic halide, to give a Pd^{IV} complex (**4**). This then loses acetate ion to regenerate the coordinated olefin (**5**) and, after migration of the aryl from Pd to olefin (**6**), β-hydrogen elimination and removal of HBr by the base (**7**) gives the required product, ArCH=CHR, and the Pd^{II} metallacycle catalyst **1** is reformed.

Martin et al. have reported a computational study on this new mechanism.¹²⁴ In their theoretical study on the Heck reaction, they explored the feasibility of this alternative pathway that involves a Pd^{II}–Pd^{IV} redox system. Quantum-chemical calculations were performed using density functional theory on a model system that consisted of diphosphinoethane (DPE) as a bidentate ligand and the substrates, ethylene and iodobenzene, to compare both mechanisms. Accordingly, the Pd^{II}–Pd^{IV} mechanism is most likely to occur in the equatorial plane of an octahedral Pd^{IV} complex. The energy profiles of both reaction pathways under consideration are largely parallel. A major difference was found for the oxidative addition of the C–I bond to the palladium centre. This is the rate-determining step of the Pd^{II}–Pd^{IV} mechanism, while it is facile for a Pd⁰ catalyst. The calculations showed that intermediate ligand detachment and reattachment was necessary in the course of the oxidative addition to Pd^{II}. Thus, the Pd^{II}–Pd^{IV} mechanism can be feasible if a weakly coordinating ligand is present.

This controversial issue of a Pd(II) and Pd(IV) intermediacy in phosphine-based palladium-catalysed Heck reactions has attracted much research interest, however, is still under debate. There is no definitive evidence yet in the literature to support this mechanism. The results published by Jones and co-workers¹²⁵ indicate that unsupported Pd species have been leached into the solution (perhaps the cause of the induction period), and the supported Pd metal centres (those still attached to the pincer ligand) are not active for the Heck coupling reaction. Furthermore, the Hg test and the polymer-supported catalytic results show that the leached species are, very likely, decomposition products of the pincer complex and not simply intact pincer species leached due to Si–O–Si bond rupture. These results support a catalytic mechanism involving Pd(0) and Pd(II) intermediates. Similar results were also observed by Herrmann¹²⁶ in the Heck reaction using a phosphapalladacycle as the catalyst.



Scheme 2. Mechanism of Heck reaction over silica-supported Pd catalysts.



Scheme 3. Pd^{II} to Pd^{IV} mechanism of Heck reaction. (a) CH₂=CHY. (b) Reversible attack of AcO⁻; attack is shown on the terminal carbon atom, but it could be on the internal carbon. (c) Oxidative addition of ArBr. (d) Reversible loss of AcO⁻. (e) Migration of Ar to terminal carbon. (f) β-Hydrogen elimination. (g) Removal of HBr by AcO⁻.

3. Silica-supported Pd complexes for Heck catalysts

3.1. Pd(II)–pincer complexes

Pincer ligands, e.g., SCS (**8**), PCP (**9**), or NCN (**10**) (Fig. 1), are defined as a tridentate structure bound to a metal. Among the most attractive palladium–ligand systems that have been supported is the Pd–pincer system.^{127–134} The use of these species for Heck reactions results in a rapid conversion of the substrate, and metal complexes based on pincer ligands have been suggested to be extremely stable.^{135,136}

Over the past decade, extensive work has been carried out on metallated pincer ligands. Advantages of pincer ligands that have been suggested in the literature include an

unprecedented stability at high temperatures, making them the candidate of choice for supported catalysis. Among the most studied pincer ligands are those illustrated in Figure 1. When metallated with a typical palladium source, all three pincer ligands contain a Pd(II) metal centre.

The literature concerning these species in the Heck reaction is somewhat muddled. Eberhard¹³⁷ has demonstrated that palladated PCP pincer complexes (**11–14**) with oxygen atoms in place of carbon in the side chains are not stable during Heck catalysis (Fig. 2). Frech et al.¹³⁸ have shown recently that the palladated pincer ligand could be reduced by sodium to form a bimetallic complex, whereas there are other publications in which immobilised PCP pincers are reported as recyclable catalysts.¹³⁵

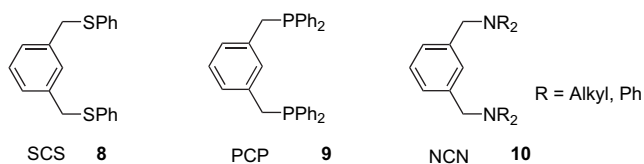


Figure 1. SCS, PCP and NCN pincer ligands.

The first syntheses of stable palladium(II) PCP-type catalysts supported on silica and their application to the Heck reaction were reported by Chanthateyanonth and Alper.¹³⁹ The commercially available 5-amino-isophthalic acid dimethyl

ester (**15**) was converted into *N*-acetyl-3,5-bis(chloromethyl)-aniline (**18**) in three steps, by reduction (**16**), acetylation (**17**) and chlorination (**18**). An Arbuzov reaction of **18** led to the diphosphine oxide (**19**). Deprotection (**20**) and functional group manipulations allowed the transformation of **19** into *N*-[3,5-bis-(diphenyl-phosphinoylmethyl)-phenyl]-succinamic acid (**21**). Subsequent reduction of **21** with HSiCl_3 afforded the diphosphine **22**, which was transformed into compound **23**. Compound **23** on reaction with a commercial aminopropyl silica gel (**24**) gave the supported complex (**25**), which on reaction with $\text{Pd}(\text{TFA})_2$ (TFA—trifluoroacetic acid), yielded Pd-silica catalyst-1 (**26**).

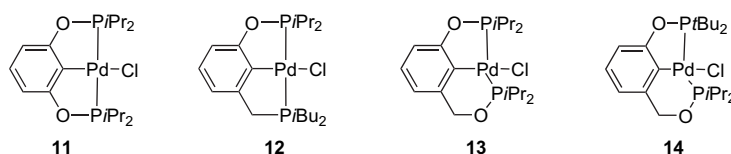
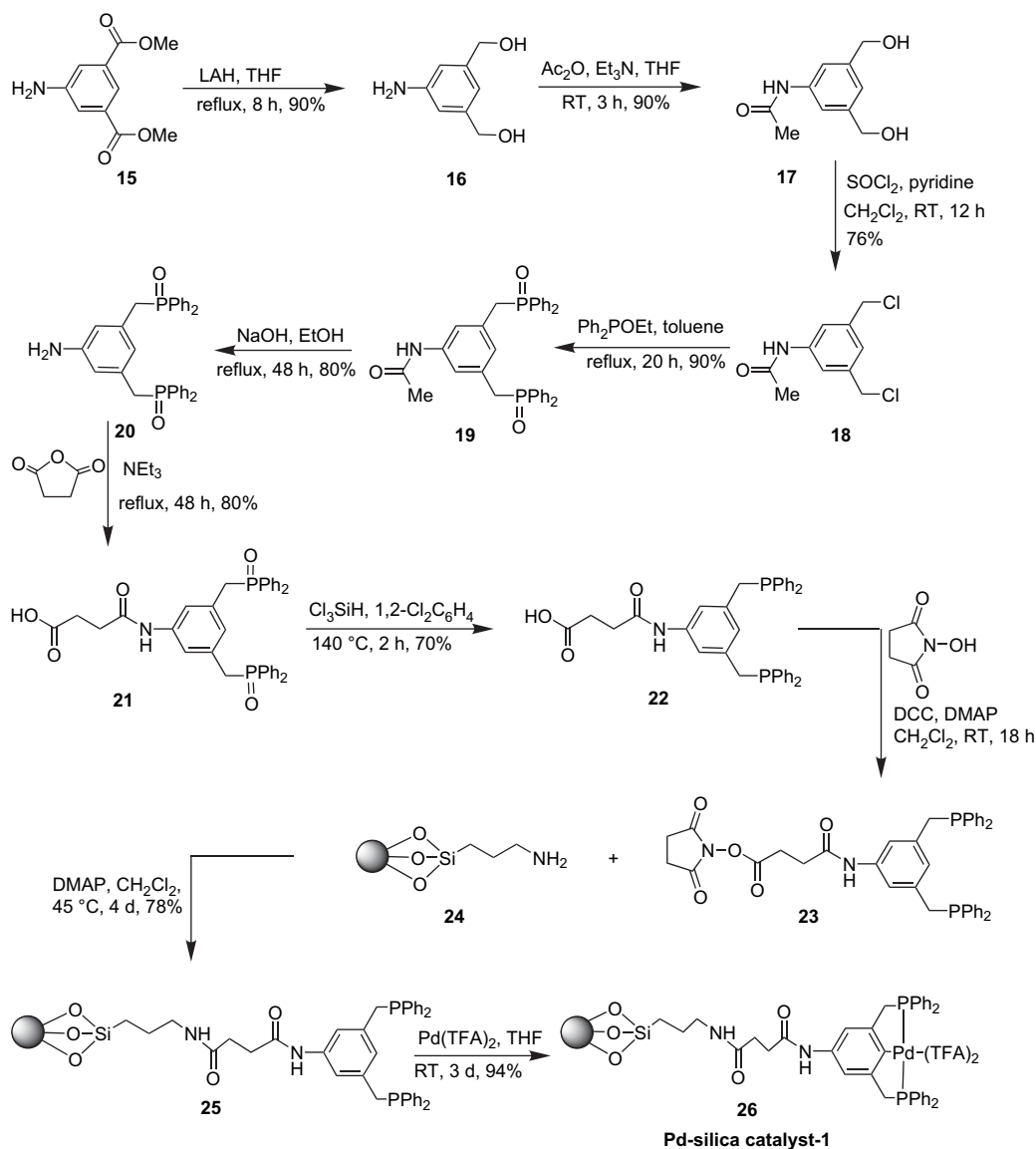
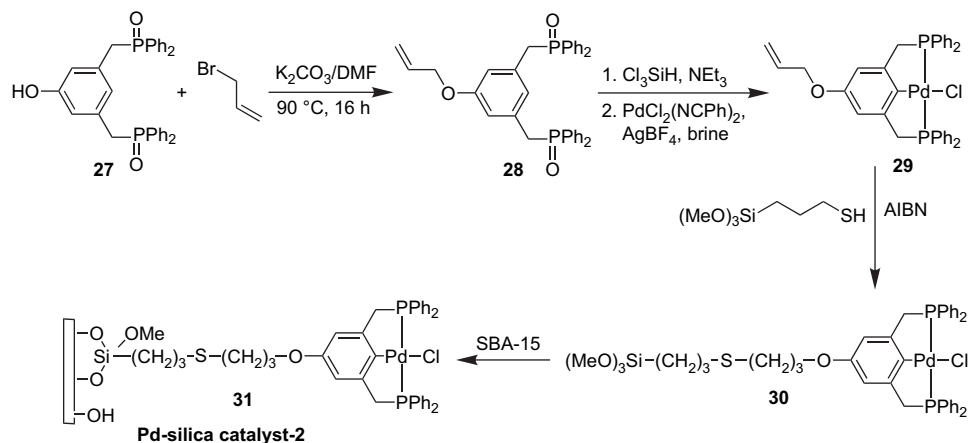


Figure 2. Palladated PCP pincer complexes.



Scheme 4. Synthesis of stable palladium(II) PCP-type catalysts supported on silica.



Scheme 5. Synthesis of Pd^{II} -PCP-type catalysts supported on silica.

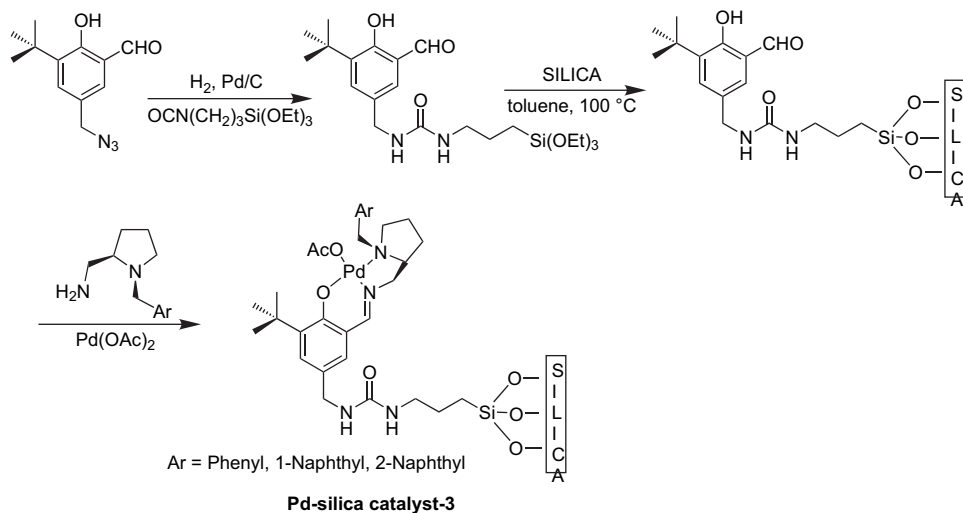
This complex shows a high catalytic activity in the Heck reaction for aryl iodides, and is also active with aryl bromides. The catalyst is thermally stable and is also stable towards oxygen and moisture. In addition, it can be recycled by simple filtration in air and re-used with only a moderate loss of activity.

Recently, Jones et al.¹²⁵ synthesised a silica-supported pincer catalyst **31** to study the influence of a heterogeneous reaction mixture on the catalysis and to compare the catalytic activity of a solid-supported system to the soluble polymer catalysts and the small-molecule analogue. To synthesise the silica-supported complex **31**, compound **27** was reacted with allyl bromide, followed by the reduction of the phosphorus in **28** using trichlorosilane and triethylamine in xylenes. Addition of $PdCl_2(NCPh)_2$ and $AgBF_4$ yielded **29** as a yellow powder. Complex **29** was then reacted with 3-mercaptopropyltrimethoxysilane and AIBN in dry chloroform to yield **30**. Complex **30** was stirred with SBA-15 silica in toluene to yield the supported pincer complex **31** (Scheme 5). Using **31** as a Heck catalyst resulted in the quantitative conversion of iodobenzene within 2 h.

These workers also studied SCS pincer complexes in a similar way¹²⁸ and observed that all complexes of this type are likely to be unstable during the Heck reaction and are therefore neither recyclable nor re-usable Heck catalysts. Recyclable catalysts may be derived from immobilised $Pd(II)$ SCS-N pincer species if, and only if, the in situ-produced $Pd(0)$ species remain wholly within the support and do not freely leach into solution.

3.2. $Pd(II)$ -Schiff-base complexes

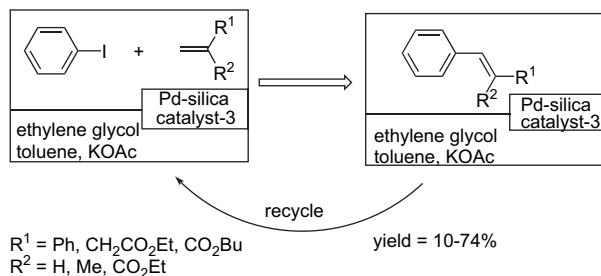
$Pd(II)$ -Schiff-base complexes heterogenised on silica-based MCM-41 were also active for catalysis in the Heck reaction. Sanchez and co-workers¹⁴⁰ prepared laminar inorganic silica with a very high specific surface ($>600\text{ m}^2/\text{g}$), which involves the use of the Schiff base, 2-*tert*-butyl-4-methyl-6{(*E*)-[1-(1-arylmethyl)pyrrolidinyl]imino}methylphenols, as anchored ligand. The heterogenised ligands reacted with palladium(II) acetate to furnish the corresponding anchored Pd complexes (Scheme 6). Notably, the metal complexes were located at the border of the inorganic silicate cups. It may then be expected that the reactant is adsorbed in the cavity of the delaminated zeolite and reacts



Scheme 6. Synthesis of $Pd(II)$ -Schiff-base catalysts supported on silica.

there with the catalyst located at the border. If this model is correct, an increase in the concentration of the reactants close to the catalytic active site should be expected and, consequently, an increase in the rate of the reaction should occur.

These workers then studied the performance of the supported Pd complexes for Heck reactions of iodobenzene using the biphasic mixture toluene and ethylene glycol, as the solvent in the presence of potassium acetate (Scheme 7).



Scheme 7. Heck reaction using Pd-silica catalyst-3.

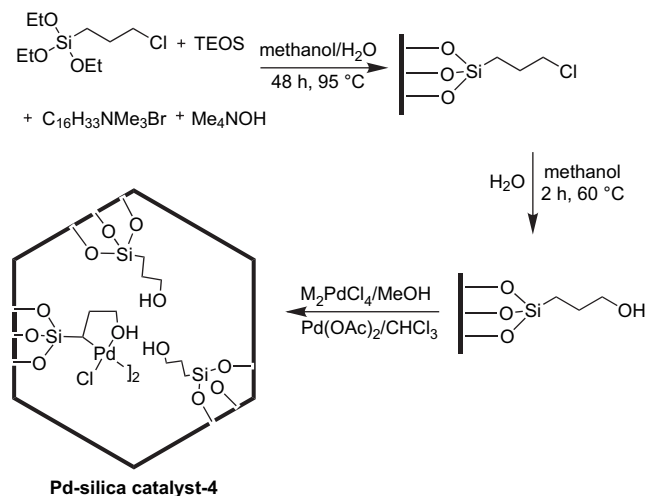
The complexes were insensitive to oxygen or moisture and no change in their activity was observed when the reaction was carried out in an open system. As expected, the bromo and iodo compounds are both active, while chlorobenzene was virtually inert. Comparative reactions have also been carried out with a homogeneous equivalent of the supported catalyst in exactly the same conditions. The initial green solution of homogeneous catalysts in NMP turned to red upon heating after the addition of base and particles of palladium black could be seen in the flask. These observations led to the hypothesis that palladium colloids will be generated upon addition of base to a solution of the homogeneous precursor when heating the reaction mixture. Indeed, upon centrifugation of the reacted mixture, these workers isolated palladium particles. These isolated particles were used in a new reaction and were found to be catalytically inactive. The absence of reactivity was presumably due to a significant aggregation of the particles under the reaction conditions. When the filtered solution was used as catalyst, it was observed that the transformation of iodobenzene does not occur.

An important point concerning the use of a heterogeneous catalyst is its lifetime, particularly for industrial and pharmaceutical applications of the Heck reaction. After separation and washing, these heterogeneous catalysts were used several times for the same reaction under the same conditions as those used for the initial run of the catalyst. An increase of activity after the first run, followed by a slight decrease of the rate, due to the small amount of catalyst lost by manipulation, was observed.

3.3. Pd(II)-carbometallated palladacycle complexes

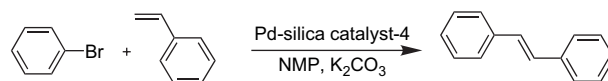
A carbometallated palladacycle was prepared on the surface the MCM-41 functionalised with 3-chloropropyltriethoxysilane.¹⁴¹ This material was synthesised by the co-condensation of TEOS (tetraethoxy orthosilicate) with 3-chloropropyltriethoxysilane followed by hydrolysis (support OH-MCM-41). A similar process yielded an OH-silica sample. Palladation was carried out over the two

functionalised supports with the palladation reagent. The generalised synthetic procedure of the palladacycle over MCM-41 is outlined in Scheme 8.



Scheme 8. Synthesis of Pd(II)-carbometallated palladacycle catalysts supported on silica.

Heck alkenylation of bromobenzene with styrene has been performed to evaluate the catalysts prepared under different reaction conditions (Scheme 9).



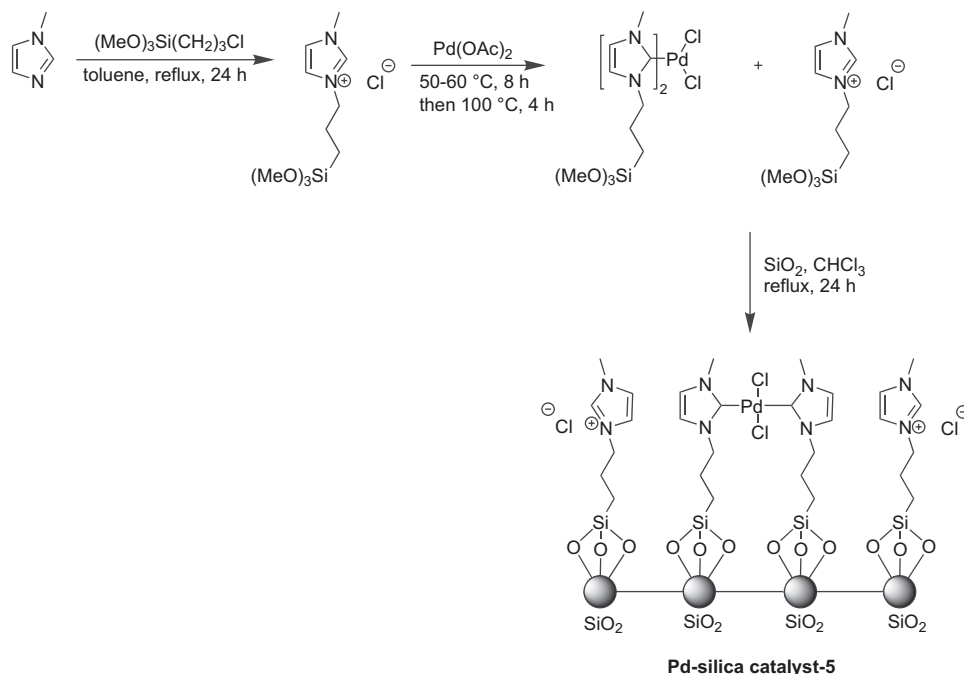
Scheme 9. Heck reaction using Pd-silica catalyst-4.

Pd-silica catalyst-4 shows a lower activity for the conversion of bromobenzene. The uptake of Pd is consequently significant in the Heck alkenylation reaction. As the reaction proceeds at the active Pd metal centre, the TON (Turnover number, with respect to Pd) varies significantly when the Pd content is changed. The Pd uptake increases in proportion to the amount of ligand (3-hydroxypropyltriethoxysilane) present in the mesoporous walls of MCM-41 and so the rate of reaction (TON) increases accordingly. A heterogeneity study reveals that the leaching of Pd from the complex into the solution is much lower (0.2 ppm) and that the catalyst worked as a heterogeneous coupling catalyst.

Karimi and Enders synthesised Pd–NHC complexes in an imidazolium-type ionic liquid matrix (which is prefunctionalised with a trimethoxysilylpropyl group) and then simultaneous grafting of the whole system on the surface of silica.¹⁴² The preparation procedure for this new concept is shown in Scheme 10. This material showed good activity with less Pd leaching in Heck reaction.

3.4. Pd(II)-non-symmetrical salen-type coordination complexes

Solid-supported catalysts derived from homogeneous palladium(II) non-symmetrical salen-type coordination complexes have been prepared and shown to be effective in the heterogeneous catalysis of carbon–carbon cross-coupling



Scheme 10. Synthesis of Pd–NHC catalysts supported on silica.

reactions.¹⁴³ These salen-type complexes were advantageous because of their simple structures with single points of attachment, taking advantage of an efficient, straightforward and inexpensive method for the synthesis of the ligands and their subsequent transition-metal complexes (Scheme 11).

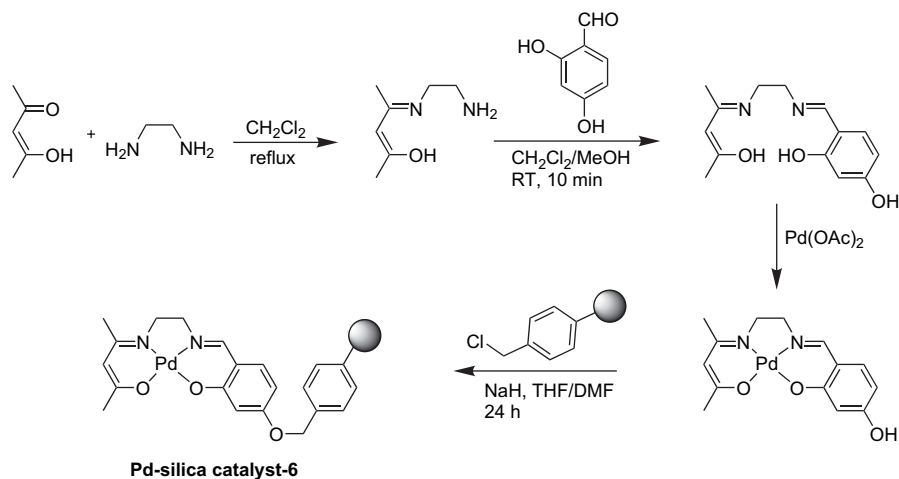
This immobilised palladium catalyst was shown to be effective in the Heck coupling without added phosphines (Scheme 12).

A comparative study between the resin and silica-supported Pd catalysts for the Heck reaction was also carried out. The activity and re-use of the silica-bound catalyst were comparable to the palladium resin. The most noticeable improvement, however, was the fact that the silica did not breakdown into a finer powder, unlike the resin, under the harsh conditions.

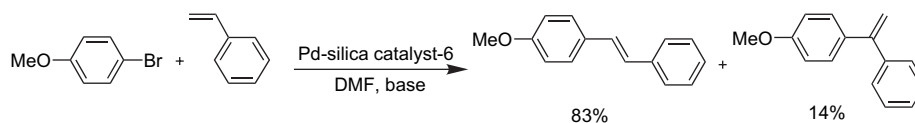
3.5. Pd(II)–thiol and Os–cinchona alkaloid complexes

Chowdari et al. synthesised a new bifunctional catalyst covalently anchored on silica, comprising Pd–thiol and Os–cinchona alkaloid complexes,¹⁴⁴ to perform Heck vinylation of aryl halides to obtain the desired prochiral olefin in situ for the asymmetric dihydroxylation to afford chiral diols successfully in a single pot.

The synthesis of the bifunctional catalyst is effected as described in Scheme 13. The silica gel support contains silanol (SiOH) groups on the surface, which could be suitably derivatised to anchor a chiral catalyst. The external surface of silica gel was treated with 3-mercaptopropyltrimethoxysilane to yield a material with mercaptopropyl tethers. The silica gel-anchored bis-cinchona alkaloid was prepared by the reaction of 4-(9-*O*-dihydroquinidiny1)-1-

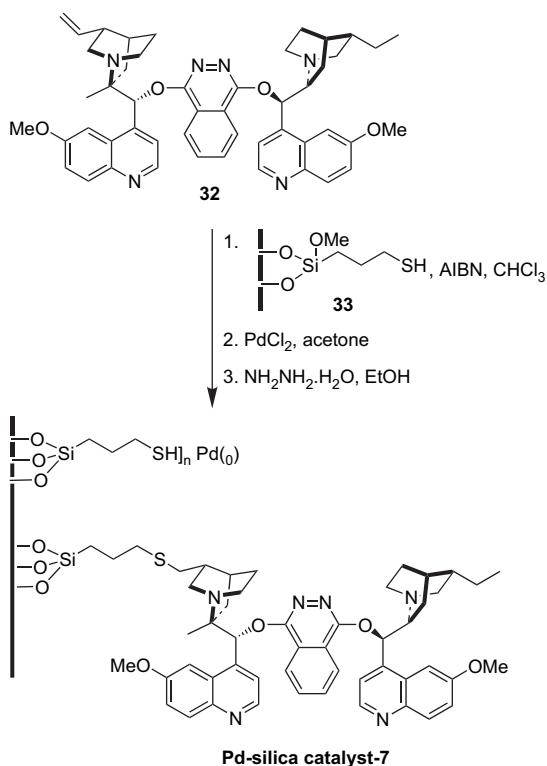


Scheme 11. Synthesis of Pd(II)-non-symmetrical salen-type catalysts supported on silica.



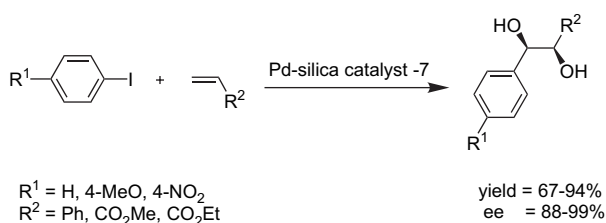
Scheme 12. Heck reaction using Pd-silica catalyst-6.

(9-*O*-quinidiny)phthalazine [(DHQD)₂PHAL] **32** with **33** in the presence of AIBN as the radical initiator in chloroform. The silica gel supported-(DHQD)₂PHAL containing SH groups was treated with PdCl₂ in acetone under reflux for 24 h. The resulting dark yellow powder was stirred with hydrazine hydrate and ethanol at room temperature for 4 h to give Pd-silica catalyst-7.



Scheme 13. Synthesis of Pd(II)-thiol and -cinchona alkaloid catalysts supported on silica.

This catalyst was then used for tandem Heck–asymmetric dihydroxylation reactions on a variety of substrates. Various disubstituted olefins were prepared in situ by the Heck reaction and subsequently subjected to asymmetric dihydroxylation in a single pot (Scheme 14).



Scheme 14. Tandem Heck–asymmetric dihydroxylation reaction using Pd-silica catalyst-7.

The use of such a bifunctional catalyst in place of a mixture of two homogeneous catalysts simplifies the catalyst recovery and purification of the products.

3.6. Pd(II) complexes via ROMP

Metathesis is nowadays among the most powerful reactions that allow the stereo- and regioselective formation of C–C bonds. For realisation of this goal on a monomeric base, ring-closing metathesis (RCM), cross-metathesis (CM), tandem metathesis and en-yne metathesis are among the most prominent reactions.¹⁴⁵ In polymer chemistry, ring-opening metathesis polymerisation (ROMP) has made the transition from a tool for specialists to a widely accepted polymerisation technique that allows the tailor-made synthesis of high-technology materials.¹⁴⁶ In this context, the capability of well-defined ROMP initiators to polymerise functional monomers in a living manner is probably among the most intriguing properties. Buchmeiser et al. used this ROMP technique for the synthesis of silica-based supports functionalised with norborn-2-ene-5-carboxyl- and 7-oxanorborn-2-ene-5-ylcarboxyl-*N,N*-dipyrid-2-ylamine dichloropalladium compounds¹⁴⁷ (Scheme 15).

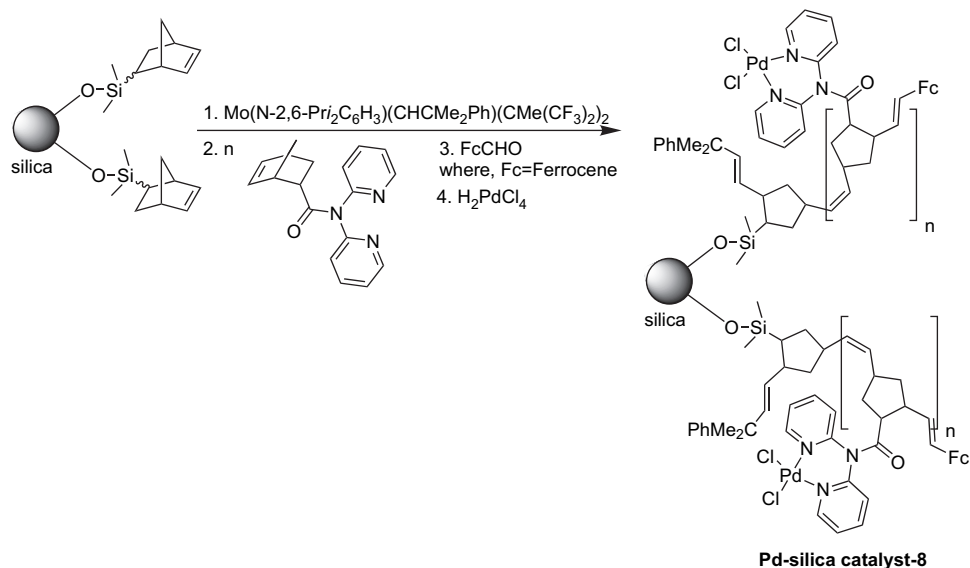
This silica-supported Pd catalyst was successfully used in flow-through reactors and for the high-throughput screening (HTS) of aryl–vinyl (C–C) Heck coupling reactions with good to excellent yield.

4. Functionalised mesoporous silica-supported palladium Heck catalysts

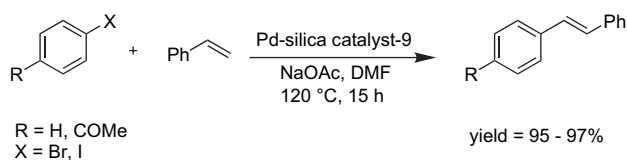
4.1. Mercapto-functionalised silica–Pd catalysts

Crudden et al.¹⁴⁸ studied mercaptopropyl-modified SBA-15 (Pd-silica catalyst-9) and examined both the ability of this material to remove various forms of Pd from aqueous and organic solutions and, most importantly, the ability of the resulting material to actually catalyse coupling reactions (Scheme 16). These workers found that not only can the mercaptopropyl-modified SBA-15 act as a scavenger for Pd, but the resulting Pd-encapsulated material can also catalyse the Heck and Suzuki–Miyaura reactions, without leaching Pd into solution. At the end of the reaction, even using loadings as high as 2%, as little as 3 ppb of Pd are observed in solution, accounting for only 0.001% of the initially added catalyst. Most remarkably, heterogeneity tests including hot filtration tests and a three-phase test have demonstrated that the catalysis occurs on the surface or in the pores of the silicate.

The catalyst was prepared by two different methods. In the first approach, (MeO)₃Si(CH₂)₃SH was reacted with a pre-formed silicate (SiO₂ or SBA-15). Functionalisation of the



Scheme 15. Synthesis of Pd(II) catalysts supported on silica via ROMP.



Scheme 16. Heck reaction using Pd-silica catalyst-9.

surface occurred by condensation with surface silanols and loss of methanol, leading to a loading of 2.2 mmol/g determined by elemental analysis. Additionally, a sol–gel synthesis in which the thiol ligand is incorporated directly into the material during its synthesis was also carried out according to Stucky's method.¹⁴⁹ For a comparison, silica functionalised with 3-mercaptopropyl groups was also prepared by grafting 3-mercaptopropyltrimethoxysilane on the surface of porous, amorphous silica.¹⁵⁰

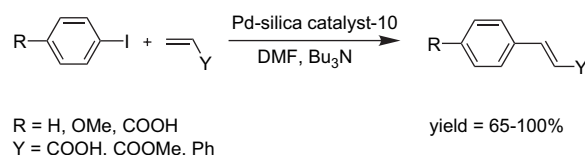
This material with an excess of thiol on the support relative to Pd exhibited a high catalytic activity for Suzuki–Miyaura and Heck reactions of bromo- and chloro-aromatics. The catalyst prepared by sol–gel incorporation of the thiol having a 4:1 S:Pd ratio was employed in catalytic runs. Interestingly, functionalised silicates prepared by grafting the thiol on the surface of preformed SBA-15 were effective scavengers, but highly capricious catalysts. In all cases, less than

1 ppm of Pd is present in the solution at the end of the reaction; in some cases, as little as 3 ppb of Pd is observed, corresponding to a loss of only 0.001% of the initially added catalyst. The heterogeneity test and the three-phase test show negligible Pd leaching.

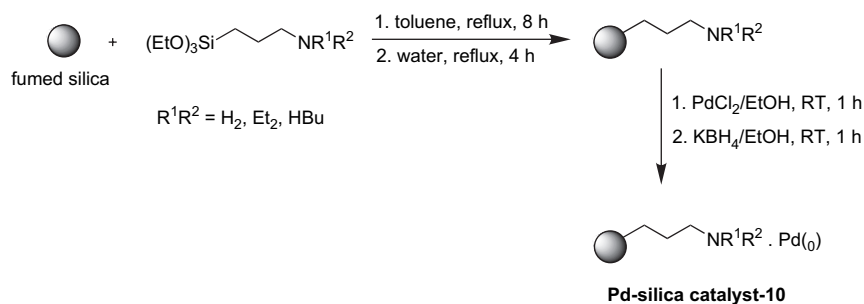
4.2. Amine-functionalised silica–Pd catalysts

A series of polymeric amine-palladium(0) complexes have been prepared from organic silica via immobilisation on fumed silica, followed by treatment with palladium chloride in ethanol and then reduction with KBH_4 in ethanol¹⁵¹ (Scheme 17).

These catalysts have a high activity for Heck arylation of aryl iodides and conjugated alkenes (Scheme 18), except the reaction of iodobenzene with methyl acrylate. A variety of substituted products were obtained in high yields with the



Scheme 18. Heck reaction using Pd-silica catalyst-10.



Scheme 17. Synthesis of amine-functionalised Pd catalyst supported on silica.

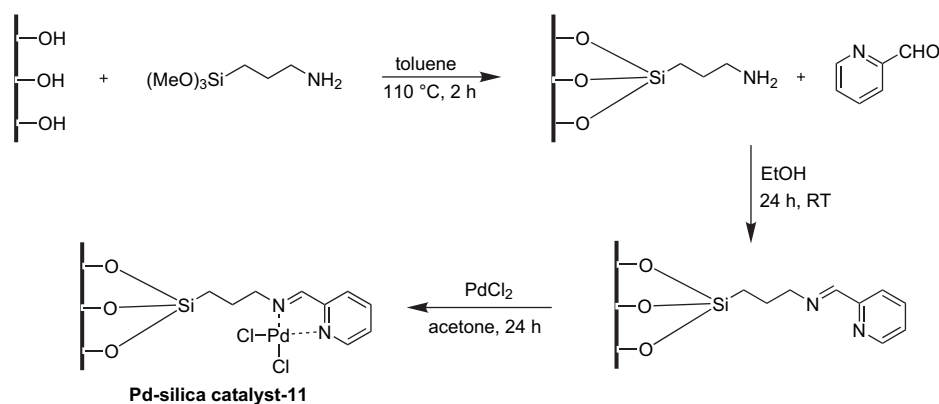
'Si'-NH₂·Pd(0) catalyst. All the olefins gave >88.7% yield. As for the arylation reaction of acrylic acid with iodobenzene, the TOF (mol product per mol Pd per hour) of 677 for the 'Si'-NHBu·Pd(0) catalyst at 90 °C is larger than that (230) at 100 °C in the corresponding Heck reaction, as reported by Cai and Song.¹⁵²

Kiviaho et al.¹⁵³ also used a functionalised silica support such as SiO₂-X-(NH)₂-Pd-L₂ (X=Sn, Al or Ti; L=PPh₃ or PhCN) for the Heck reaction. The activity of the supported catalyst was in the order: SiO₂-Sn-(NH)₂>SiO₂-Al-(NH)₂>SiO₂-Ti-(NH)₂.

4.3. Pyridine-functionalised silica-Pd catalysts

Nitrogen chelating ligands have been shown to be an effective replacement for phosphine ligands in Heck-type reactions. In addition, these ligands are air stable, less expensive and non-toxic. Palladium complexes immobilised on silica functionalised with acetylpyridines⁷² have been found to be active and stable catalysts in the Heck reaction of iodobenzene with ethyl acrylate (TON of 350 mmol ethyl cinnamate/mmol Pd in the first cycle and 4100 mmol ethyl cinnamate/mmol Pd for the 14th cycle in Heck reaction of iodobenzene with ethyl acrylate), as well as in the carbonylation of iodobenzene. Clark et al.⁷⁰ have reported C-C coupling of iodobenzene using pyridinium-palladium complexes immobilised on MCM-41 with a minimal level of palladium leaching and TONs of around 2000 mmol of methyl cinnamate/mmol Pd in the fifth cycle. High catalytic activities, selectivities and stabilities have been reported in the Heck reaction catalysed by pyridine-functionalised silica-supported palladium catalysts.^{70,154,155}

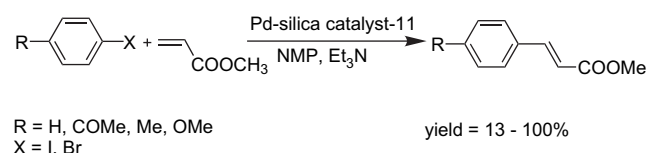
Sugi et al.¹⁵⁶ prepared palladium complexes immobilised on pyridine-carboimine- and quinoline-carboimine-functionalised mesoporous FSM-16. These immobilised complexes can be sufficiently applied for the Heck vinylation and even for the Suzuki coupling of aryl bromides as active and re-usable catalysts with a minimal leaching of palladium species into solution and with stability at higher reaction temperatures using quinoline-carboimine as ligand can offer higher conversions than pyridine-carboimine. Immobilisation of palladium complexes on FSM-16 consists of the following steps, as illustrated in Scheme 19:



Scheme 19. Synthesis of pyridine-functionalised Pd catalyst supported on silica.

- surface modification of FSM-16 with 3-aminopropyltrimethoxysilane;
- preparation of pyridine and quinoline-carboimine ligands on FSM-16; and
- preparation of palladium complex on FSM-16 with PdCl₂.

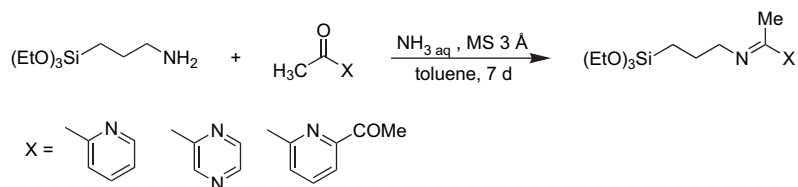
The activity of these palladium complexes immobilised on FSM-16 was tested in the Heck reaction of aryl halides, namely the reactivity of aryl iodides and bromides with methyl acrylate in polar and non-polar solvents using triethylamine as a base (Scheme 20). Addition of quaternary ammonium salts is often used to enhance the reactivity and selectivity of the Heck reactions.^{48,76,80,157,158} Bu₄NBr was used as an additive (15 mol % based on aryl bromide) in the Heck vinylation of aryl bromides with electron-donating substituents over this catalyst, which effectively increases the reaction rate and yield of the desired products.



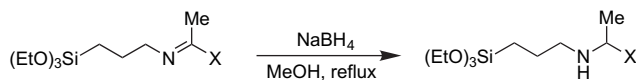
Scheme 20. Heck reaction using Pd-silica catalyst-11.

Lagasi and Moggi also tested Pd complexes of silica-anchored, nitrogen-containing chelating compounds for the Heck reaction of iodobenzene with ethyl acrylate or styrene.⁷² These complexes were prepared by the following reactions.

- Synthesis of the Schiff bases from 3-aminopropyltriethoxysilane and 2-acetylpyridine, 2-acetylpyrazine or 2,6-diacetylpyridine (Scheme 21).
- Reduction of the Schiff bases with NaBH₄ in methanol (Scheme 22).
- Cogelification with tetraethyl orthosilicate (TEOS): (EtO)₃Si(CH₂)₃NHCH(Me)X was then reacted with Si(OEt)₄ in a 1:9 mole ratio in ethanol/water using ammonia as a catalyst. The three functionalised silica gels prepared from 2-acetylpyridine (SILPY) **34**, 2-acetylpyrazine (SILPZ) **35** and 2,6-diacetylpyridine (SIL-DIPY) **36** are shown in Figure 3.



Scheme 21. Synthesis of Schiff bases.



Scheme 22. Reduction of the Schiff-bases.

(d) Reaction of the functionalised silica with $[\text{PdCl}_2(\text{PhCN})_2]$: To prepare the anchored palladium complexes, $[\text{PdCl}_2(\text{PhCN})_2]$ was dissolved in CH_2Cl_2 and the calculated amount of the functionalised silica

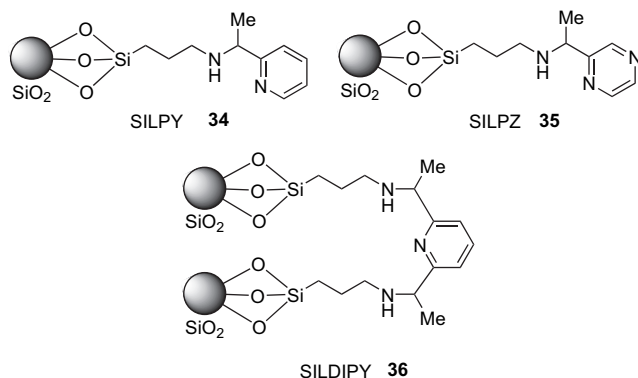


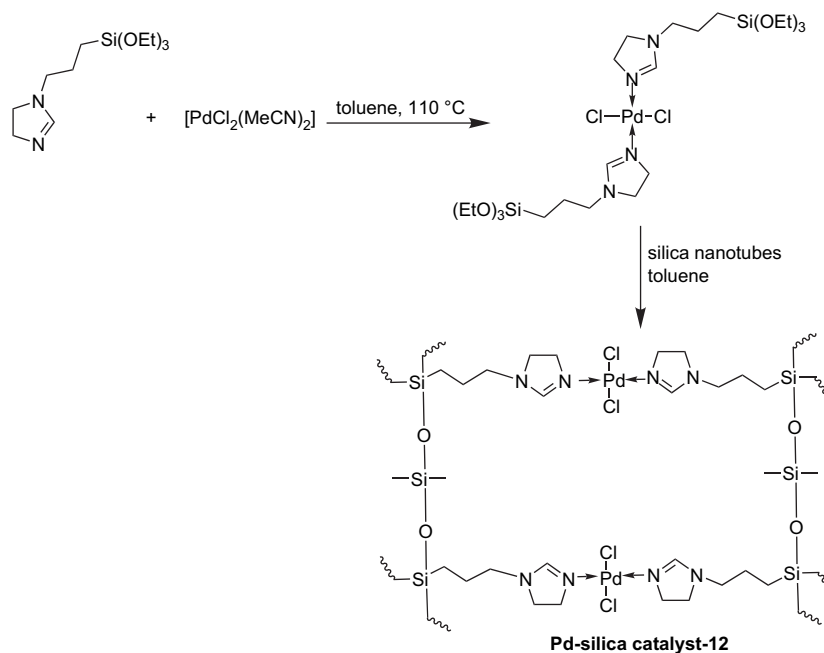
Figure 3. Functionalised silica gels: SILPY, SILPZ and SILDIPY.

was added. The suspension was maintained for 4 h under stirring, and the only physically adsorbed complex was then extracted in a Soxhlet apparatus with refluxing CH_2Cl_2 for 3 h. The solid was finally dried overnight at 50°C in vacuum. This functionalised silica-anchored Pd(II) was reduced to the metal Pd(0) by a suspension of NaBH_4 in methanol.

These Pd catalysts were then used successfully for the Heck reaction of iodobenzene with ethyl acrylate or styrene. The catalysts were separated from the reaction mixtures and re-used many times. The best results were obtained in Heck reactions with the anchored Pd complexes prepared from 2-acetylpyridine: 14 cycles in the Heck reaction (TON=4100 mmol product/mmol Pd).

4.4. Imidazole-functionalised silica–Pd catalysts

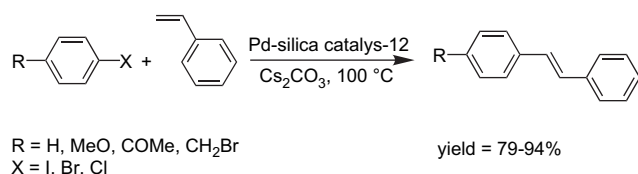
A mesoporous silica-nanotube-supported 3-(4,5-dihydroimidazol-1-yl)-propyltriethoxysilane-dichloropalladium(II) complex was prepared and tested for catalytic activity for Heck coupling reactions between styrene and several aryl halides.¹⁵⁹ The dichloro-3-(4,5-dihydroimidazol-1-yl)-propyltriethoxysilane-palladium(II) catalyst was prepared from 3-(4,5-dihydroimidazol-1-yl)-propyltriethoxysilane and $\text{PdCl}_2(\text{MeCN})_2$ in toluene, as shown in Scheme 23. The results showed that three different morphological classes of silica



Scheme 23. Synthesis of imidazole-functionalised Pd catalysts supported on silica.

xerogels were synthesised. Completely amorphous silicates were obtained in the presence of alcohols, whereas the material originating from DL-tartaric acid was silica nanotube in a morphological state. Non-porous silica sphere formation was noticed along with the nanotube formation. As expected, the silica nanotubes had the smallest BET (Brunauer–Emmett–Teller) area. The pore size distribution, calculated by the BJH method, indicates that the nanotubes can be considered as essentially macroporous materials, whereas the majority of the pores in the amorphous silica and silica foams fall into the mesoporous range.

Pd-silica catalyst-12 was found to be an active catalyst for the Heck reaction and proved to be thermally robust for high-temperature Heck olefination of aryl chlorides, bromides or iodides (Scheme 24).



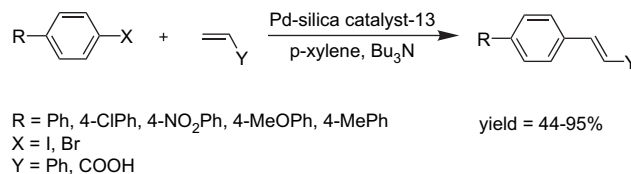
Scheme 24. Heck reaction using Pd-silica catalyst-12.

4.5. Poly-3-(diphenylarsino)propylsiloxane-functionalised silica–Pd catalysts

A silica-supported poly-3-(diphenylarsino)propylsiloxane-palladium(0) complex has been prepared from 3-chloropropyltriethoxysilane via immobilisation on fumed silica, followed by reaction with potassium diphenylarsenide in THF and palladium chloride in acetone, and then reduction with hydrazine hydrate in ethanol¹⁶⁰ (Scheme 25).

This Pd-silica catalyst-13 was found to be a highly active and stereoselective catalyst for arylation of conjugated alkenes with aryl halides, affording a variety of unsymmetrical

(*E*)-stilbenes and substituted (*E*)-cinnamic acids in high yields (Scheme 26). The polymeric palladium catalyst can be recovered and re-used easily.



Scheme 26. Heck reaction using Pd-silica catalyst-13.

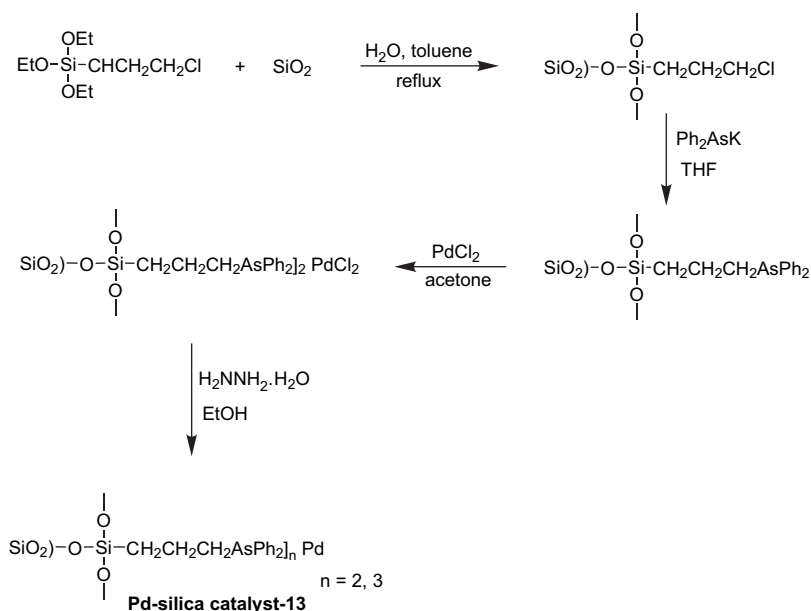
4.6. Poly-3-(methylseleno)propylsiloxane-functionalised silica–Pd catalysts

A silica-supported poly-3-(methylseleno)propylsiloxane-palladium complex has been prepared from 3-chloropropyltriethoxysilane via immobilisation on fumed silica, followed by reaction with sodium methylselenolate and then with palladium chloride (Scheme 27). It is an efficient catalyst for Heck carbonylation of aryl halides under an atmospheric pressure of carbon monoxide.¹⁶¹

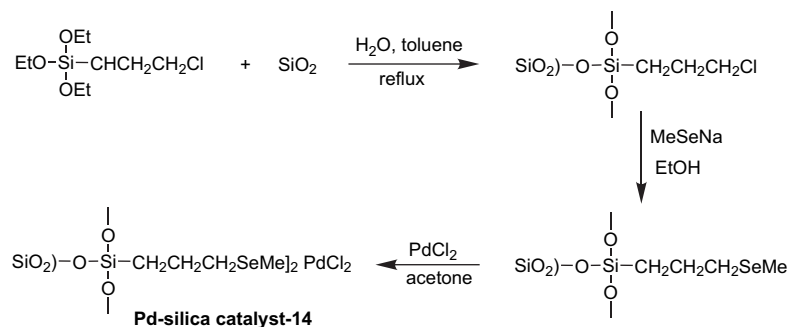
4.7. Poly-11-(methylseleno)undecylsiloxane-functionalised silica–Pd catalysts

The silica-supported poly-11-(methylseleno)undecylsiloxane-palladium(0) complex was studied for the Heck arylation of conjugated alkenes with aryl halides.¹⁶² This complex was conveniently prepared from 11-chloroundecyltriethoxysilane via immobilisation on fumed silica, followed by reaction with sodium methylselenolate in ethanol and palladium chloride in acetone, and then reduction with hydrazine hydrate in ethanol (Scheme 28).

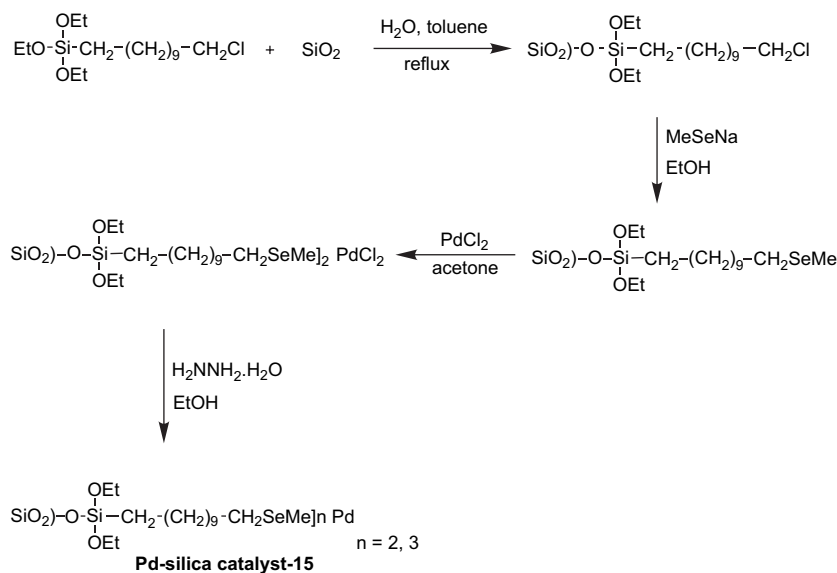
This complex has a high activity and stereoselectivity for arylation of conjugated alkenes with aryl halides (Scheme 29).



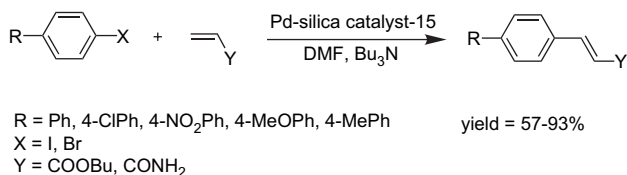
Scheme 25. Synthesis of poly-3-(diphenylarsino)propylsiloxane Pd catalysts supported on silica.



Scheme 27. Synthesis of poly-3-(methylseleno)propylsiloxane Pd catalysts supported on silica.



Scheme 28. Synthesis of poly-11-(methylseleno)undecylsiloxane Pd catalysts supported on silica.



Scheme 29. Heck reaction using Pd-silica catalyst-15.

When Pd-silica catalyst-15 was used in four consecutive runs for the arylation reaction of butyl acrylate with iodobenzene, (*E*)-butyl cinnamate was formed in 90, 88, 87 and 85% yield.

4.8. Structural investigations of functionalised mesoporous silica-supported Pd catalysts

The stability of the Pd catalyst is also important for the large-scale industrial application of the coupling reactions. It is generally assumed that the deactivation of the Pd complex occurs via aggregation of palladium intermediates to clusters and further to inactive large metallic particles (Pd black). To overcome these problems, it is highly desirable to develop heterogeneous catalysts having a high stability and recyclability.

Shimizu et al.¹⁶³ carried out structural investigations of functionalised mesoporous silica-supported palladium

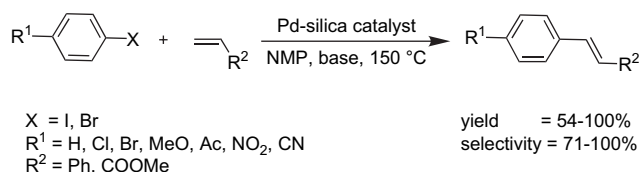
catalysts such as Pd-SH-FSM, Pd-SiO₂-SH, Pd-FSM, Pd-Y and Pd/C for Heck coupling reactions. The stability towards the formation of inactive Pd metal particles is the crucial factor for achieving a stable heterogeneous catalysis for Heck reactions. The structural stability of Pd species can be controlled by using the appropriate support. As for the conventional catalysts (Pd/zeolite and Pd/C), the Pd(II) species highly dispersed in the Na-Y zeolite or on the activated carbon are aggregated to form less active metallic particles or clusters. In contrast, the silica-immobilised SH groups act as polydentate ligands to stabilise Pd(II) species during Heck reactions. The sulfur ligands in the size-restricted mesopores of FSM-16 were the most effective for preventing the Pd metal aggregation, which results in high durability and recycling characteristic of the Pd-SH-FSM. This catalyst provides a clean and convenient alternative for Heck reactions, because of its heterogeneous nature, high durability (high TON), simple reaction procedures and recyclability without a marked loss of the catalytic activity.

Köhler et al.⁹⁹ also investigated the Heck reaction of the readily available aryl bromides with olefins catalysed by palladium supported on a wide variety of different supports. They found that palladium supported on metal oxides and zeolites exhibits high activity and selectivity in the

formation of carbon–carbon bonds by arylation of olefins (Heck reaction). Analogous to homogeneous Heck catalysis, the gradation of the aryl bromide conversion depends on the activation of the aryl bromide by an electron-withdrawing substituent in the *para*-position to the bromine and the electron density of the olefin π -bond. Activated aryl bromides show complete turnover at 140 °C after a few hours using the heterogeneous catalysts. The activity of the catalysts can be correlated with the nature of the support and the palladium dispersion. For supports being ‘inert’ with respect to the Heck reaction (SiO₂, carbon), the activity (conversion, yield) is directly connected to the Pd surface area. A second group of catalysts shows a higher activity than expected from their Pd dispersion (MgO and other basic oxides). Pd on TiO₂ (transition metal oxides) shows an inverse correlation between activity and Pd surface area.

5. Sol–gel entrapped silica–Pd catalysts

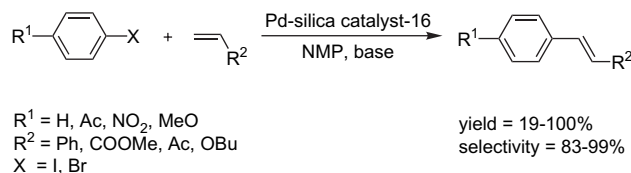
Molnar et al.¹⁶⁴ prepared sol–gel entrapped Pd-silica catalyst-15. These catalysts were generated via simultaneous self assembling of mesoporous MCM-41 silica and particle generation. Three catalysts with palladium loadings of 1.39, 3 and 5.85% based on inductively coupled plasma atomic emission spectroscopy (ICP-AES) were prepared and characterised by various physical methods. BET surface areas of the samples calculated by the BJH method were found to decrease (1099, 979 and 806 m²/g, respectively) with increasing palladium loading, whereas pore diameters and d_{100} indexed unit-cell sizes determined by low-angle XRD increased slightly. Pd dispersion values measured by hydrogen chemisorption were 8.2, 5.7 and 13.6%, respectively. All three catalysts showed high activity and selectivity in the Heck coupling of iodobenzene with styrene (76–84% conversions and 84–87% selectivities) and methyl acrylate (89–100% conversions and 100% selectivities). Moreover, activities in the transformation of activated bromoarenes were also satisfactory. In all reactions complete *E* selectivity was observed, whereas in the transformations of styrene, products of α -coupling were found (Scheme 30). It was also found that activities depend on palladium loadings and parallel metal dispersion. In most cases the catalytic performance of 3.0% Pd–MCM-41 with the lowest Pd dispersion (5.7%) showed a lower activity. Aromatic chloro compounds were found not to react.



Scheme 30. Heck reaction using Pd-silica catalyst.

Molnar et al. also prepared various other supported catalysts (Pd-silica catalyst-16) using trichlorosilane, dichloromethylsilane, chlorodimethylsilane, dichlorophenylsilane or chlorodiphenylsilane, which can be denoted as SiO₂, SiO₂Me, SiO₂Me₂, SiO₂Ph and SiO₂Ph₂, respectively.¹⁶⁵ These five Pd-on-silica catalysts were applied in the reaction

of iodo- and bromo-arenes with styrene and aliphatic vinylic compounds (Scheme 31).



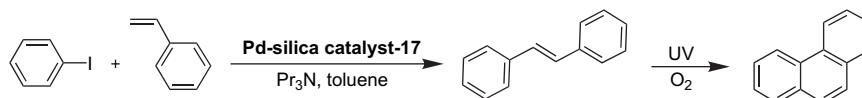
Scheme 31. Heck reaction using Pd-silica catalyst-16.

All catalysts proved to be active in the Heck coupling. The conversion values were between 19 and 100%, whereas the selectivities were found to be in the range 83–99%. It was significant that even less reactive activated bromoarenes such as *p*-bromoacetophenone and *p*-bromonitrobenzene react satisfactorily with methyl acrylate. Bromobenzene and chlorobenzene, in turn, do not react. Furthermore, the highly selective formation of the corresponding *E* isomers is characteristic in all cases.

Recovery and catalyst re-use are important issues in the Heck coupling. Easy catalyst separation and recycling in successive batch operations can greatly increase the efficiency of the reaction. Reports exist, which show some success in this respect using immobilised complexes and heterogeneous catalysts with metallic species in a limited number of re-uses. It was observed that heterogeneous Pd catalysts with organic–inorganic hybrid supports exhibit promising characteristics in recycling studies. A catalyst was re-used 20 times without any loss of activity.

Blum et al. also employed a sol–gel entrapped version of the PdCl₂(PPh₃)₂ catalyst for the Heck coupling process.¹⁶⁶ This heterogeneous catalyst is characterised by extremely simple preparation. It is a perfectly leachproof, highly porous material (typical N₂-BET surface areas of 490 m²/g and average pore diameters of 27 Å) and is completely air stable for many months.

A large increase in the Heck reaction rate was attributed to the slow modification and activation of the entrapped palladium compound in the presence of alkynes. In addition the entrapment of catalysts within sol–gel matrices not only permits the facile recycling of the dopant but also protects it from hostile and opposing chemicals. This is suitable to conduct multistep one-pot reactions with entrapped catalysts in the presence of (separately) entrapped catalyst poisons and with acidic catalysts in the presence of bases, to perform simultaneously oxidation and catalytic hydrogenation, and to carry out esterifications by sol–gel entrapped lipase in the presence of an enzyme-destroying metallic catalyst.¹⁶⁷ This study was extended by Malloy to the photocyclisation of stilbenes.¹⁶⁸ The combination of a Heck vinylation with photolysis in two separate steps has been employed in the syntheses of various polycyclic derivatives.¹⁶⁹ With the aid of sol–gel entrapped PdCl₂(PPh₃)₂ (Pd-silica catalyst-17), the authors were able to carry out the two-step reaction shown in Scheme 32 in one pot. It should be noted, however, that the activity of the free PdCl₂(PPh₃)₂ as a Heck coupling catalyst decreases during irradiation of iodobenzene, while that of the entrapped complex was not affected.

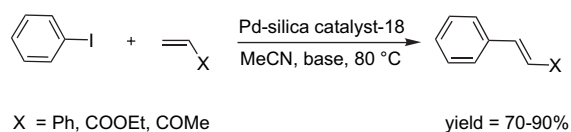


Scheme 32. Heck reaction using Pd-silica catalyst-17.

6. Nanosized Pd particles embedded in silica catalysts

Different nanocomposite silica aerogels were synthesised using anhydrous Pd(acac)₂ as the metal source (Pd-silica catalyst-18).¹⁷⁰ No reduction step is required to obtain metallic particles of Pd(0). In all cases tetraethoxysilane was employed as the silica source. The silica wet gels were prepared in a two-step, acid–base-catalysed sol–gel process and impregnation of the wet gels was then carried out. By sol–gel synthesis, the host matrix is formed as the result of hydrolysis–condensation reactions from an alkoxide, water, a mutual solvent and a catalyst. Silica aerogels (825 m²/g) containing 3.7% of palladium nanoparticles were obtained by the same method. The powder X-ray diffraction (XRD) pattern obtained for the Pd–SiO₂ aerogel was characteristic of the metallic fcc (face cubic centre)-Pd phase. No reduction step was used in the preparation of this nanocomposite. It has been previously assumed by some authors that during the drying process in the autoclave, the EtOH at high temperature is responsible for the reduction of the Pd²⁺.¹⁷¹

Curiously enough, the micrograph of the precarbonised material having 21 wt % of Pd showed particles with diameters between 6 and 10 nm. The Pd(0)-containing materials were tested as catalysts in Heck reactions. For all the Heck reactions, 2 mol % of palladium with respect to the limiting reagent and triethylamine as a base in refluxing MeCN were used (Scheme 33). For Pd-doped aerogels, better results were obtained for the Pd-organic, having a smaller Pd(0) particle size (8 nm), than for the Pd–carbon aerogel (19 nm).



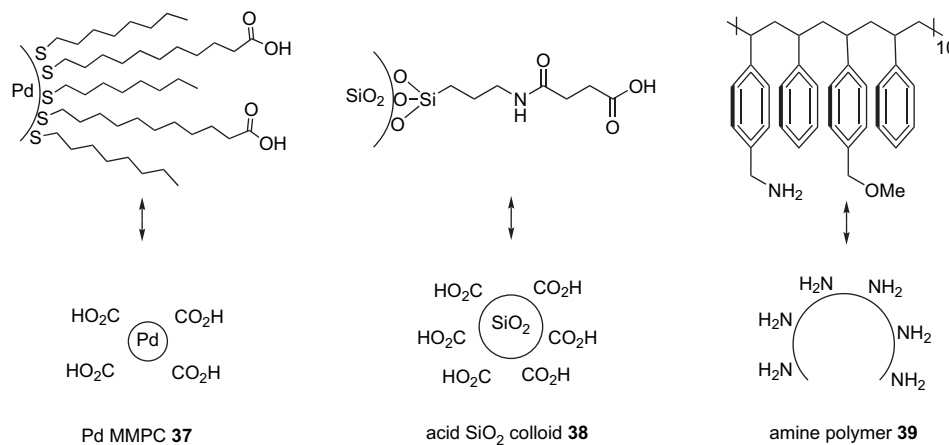
Scheme 33. Heck reaction using nanosized Pd-silica catalyst-18.

Kim et al. also prepared the silica gel entrapping palladium nanoparticles through a two-step procedure by heating a mixture of Pd(PPh₃)₄, tetra(ethylene glycol), and Si(OMe)₄ and treating the resulting black suspension with water. Washing and drying the resulting gel gave a grey powder that was used as the catalyst in the Heck reaction.¹⁷²

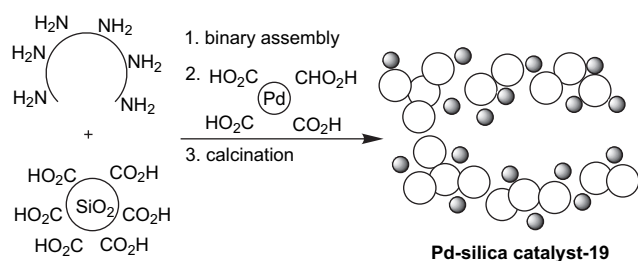
The high surface area-to-volume ratio of noble metal nanoparticles makes them highly attractive tools for catalysis. One key challenge in the application of these particles is agglomeration. While aggregation can be overcome through surface functionalisation,^{173,174} this introduces mass transport issues that limit the catalytic efficiency of the catalytic system. Heterogeneous noble metal catalysts, on the other hand, are typically prepared by deposition of the metal onto preformed supports,^{175,176} resulting in limited control over the metal particle size and dispersion. The use of directed self-assembly to construct heterogeneous catalysts in a bottom-up fashion presents a promising alternative, preventing agglomeration while providing the inherent advantages of heterogeneous catalysts, such as ease of product separation and catalyst recycling.

Mixed monolayer protected clusters (MMPCs)¹⁷⁷ are inherently versatile building blocks for self organisation. MMPCs bearing recognition moieties in the monolayer can be assembled into macroscopic aggregates through the use of suitable mediators.^{178,179} This electrostatically mediated assembly process was used by Rotello et al. for the creation of highly reactive, recyclable, heterogeneous catalysts in which palladium MMPCs are simultaneously used as building blocks and active catalytic units.¹⁸⁰

The required SiO₂ building block **38** and polymer **39** (Fig. 4) were synthesised using established procedures.^{178,179} The Pd nanoparticles **37** were fabricated by positional exchange of 11-mercaptoundecanoic acid onto 1-nm octanethiol-covered particles.¹⁸¹

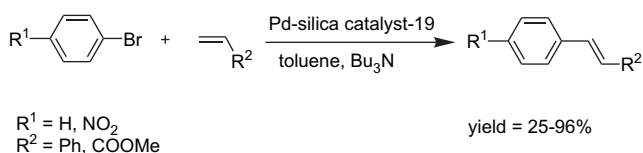
Figure 4. Pd MMPC, acid SiO₂ colloid and amine polymer.

MMPC **37** was dissolved in MeOH to 2.4% w/v, and the silica particles **38** and polymer **39** were dissolved in DMF to 12 and 6% w/v, respectively. Mixing the polymer **39** with carboxylic acid–silica colloids **38** followed by addition of **37** afforded the ternary systems via acid–base reaction followed by immediate charge pairing (Scheme 34). The order of addition provides control over the distribution of the metal component; addition of the palladium colloid to a preformed silica colloid–polymer aggregate should lead to high concentrations of the metal near the surface of the final aggregates. Transmission electron microscopy (TEM) images of precalcined aggregates reveal highly open micron-scale superstructures. The active catalysts were prepared through calcination of the nanocomposite materials. Significantly, after calcination, the highly porous nature of the systems remained intact.



Scheme 34. Synthesis of silica gel entrapped palladium nanoparticles.

The utility of this nanocomposite catalyst was tested for Heck carbon–carbon bond-formation reactions and good results were obtained for coupling activated and electronically neutral bromoarenes with styrene and methyl acrylate (Scheme 35).

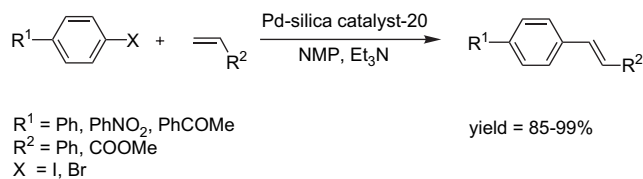


Scheme 35. Heck reaction using Pd-silica catalyst-19.

As expected, the nitroarene coupled most efficiently, requiring only 0.045 mol % of Pd, a dramatic improvement over the commercial counterparts, Pd/C and Pd/SiO₂. Most importantly, the catalyst required no activation, no toxic ligand, and could be recycled with only a small decrease in activity.

7. Colloid palladium layer–silica catalysts

A palladium colloid layer on the pore channel surface of mesoporous silica (Pd-SBA-15) was also used as heterogeneous catalyst (Pd-silica catalyst-20) in the Heck reactions.^{182,183} This hexagonally packed porous Pd-SBA-15 material was investigated with activated and non-activated aryl halides, with styrene and methyl acrylate as the vinylic substrate. The yields for the aryl halides with respect to the reaction time and the amount of catalyst showed that the Pd-SBA-15 catalyst has an excellent activity for Heck carbon–carbon coupling reactions (Scheme 36).



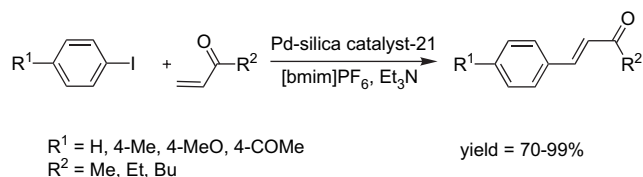
Scheme 36. Heck reaction using Pd-silica catalyst-20.

These modified materials showed very high stability against leaching of the active species into the liquid phase under the given reaction conditions. This feature is important for a heterogeneous catalyst system. Compared to the analogous Pd-modified catalyst Pd-TSM1, which was synthesised by the CVD (chemical vapour deposition) method,⁹⁷ Pd-SBA-15 shows a relatively high catalytic activity in Heck reactions. It only needs about 20% of the amount of catalyst to reach the same conversion under the same reaction condition. This is due to the high dispersion of Pd in the form of ultra thin colloid layers in the channels of the host and the absence of large Pd clusters on the outer surfaces of the Pd-SBA-15 particles.

8. Silica/ionic liquid Pd catalysts

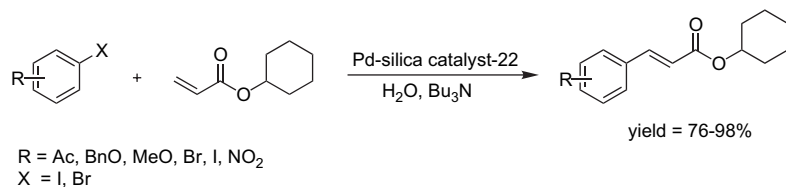
Ionic liquids (ILs) as environmentally acceptable solvents for organic reactions have also attracted attention in recent years, because they have a very low vapour pressure and can be used to replace organic solvents. Among them, imidazolium-based ionic liquids have been extensively utilised as reaction media for a number of palladium-catalysed coupling reactions that, in fact, act as *in situ* imidazole carbene ligands with transition metals.^{61,184,187}

Yokoyama et al. obtained high conversions of the Heck reactions in ionic liquid [bmim]PF₆ (bmim=*N*-butyl *N*-methyl imidazole) with a non-reduced Pd(II)/SiO₂ catalyst (Pd-silica catalyst-21) and 2 equiv of triethylamine and without phosphine ligands at 375 K¹⁸⁸ (Scheme 37).



Scheme 37. Heck reaction using Pd-silica catalyst-21 in an ionic liquid.

Suzuki et al. investigated a facile immobilisation of the Pd catalyst in an ionic liquid in silica pores for use in sustainable Heck reactions with high efficiency and recyclability.¹⁸⁹ Immobilisation of the Pd catalyst on silica with the aid of an ionic liquid should provide the following features: (1) stabilisation of the Pd catalyst, (2) inexpensive immobilisation without using expensive coupling reagents or a large amount of the ionic liquid, and (3) accumulation of Pd on silica to facilitate catalytic reaction. The procedure of immobilisation is quite simple and involves a suspension of spherical amorphous silica in a solution of Pd(OAc)₂ in [bmim]PF₆ and THF being evaporated to dryness to afford a powdery and free-flowing immobilised catalyst.

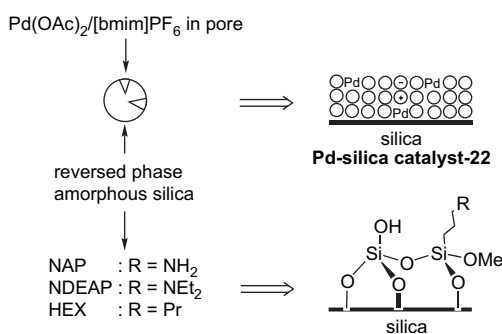


Scheme 38. Heck reaction using Pd-silica catalyst-22.

Among the ionic liquids tested, [bmim]PF₆ was better at holding Pd(OAc)₂ than [bmim]Br, [bmim](CF₃SO₂)₂N, or [hmim]PF₆ (hmim=*N*-hexyl *N*-methyl imidazole). To prevent removal of the ionic liquid layer from the silica, the Heck reaction was carried out in a hydrocarbon solvent. Re-use of the catalyst was difficult in hot toluene, due to the solubility of the ionic liquid. A decrease of the catalytic activity was observed after three cycles, during which the free-flowing nature of the catalyst was lost.

A similar reaction was also carried out in water as a solvent¹⁹⁰ (Scheme 38). The major advantage in carrying out the reaction in water is its non-flammable, inexpensive and non-toxic nature. There is no need to desiccate substrates prior to the reaction. Other advantages are the high cohesive energy density (c.e.d.; 550 cal/cm³), high dielectric constant and high internal pressure, which might facilitate bimolecular reactions involving ionic intermediates. Furthermore, the use of a heterogeneous catalyst is expected to increase the Heck reaction rates by adsorption of substrates on the catalyst. Compared to the reaction in dodecane, the reaction was apparently accelerated in water, since it was completed at a lower temperature and in a shorter period of time.

An attempt to recycle the catalyst, however, resulted in the unexpected removal of the ionic liquid layer from the silica gel into the aqueous layer, resulting in leaching of the Pd. Water entered between the ionic liquid layer and the silica gel surface, probably due to the hydrophilic nature of the latter. This problem was overcome by the immobilisation of Pd(OAc)₂ on reversed-phase silica gels, among which hexylated (HEX), aminopropylated (NAP) and *N,N*-diethylaminopropylated silica gel (NDEAP) were employed (Scheme 39). These silica gels were easily obtained by grafting with the corresponding silane coupling reagents.¹⁹¹ Pd(OAc)₂ was successfully immobilised on each of the reversed-phase silica gels, except HEX, with the aid of [bmim]PF₆. The reactivity of these immobilised catalysts was tested in the reaction of iodobenzene and cyclohexyl acrylate. The reaction

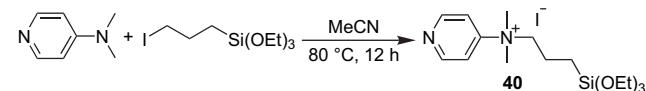


Scheme 39. Synthesis of Pd catalyst in an ionic liquid in silica pores.

was sluggish, as compared to the catalyst immobilised on normal phase silica gel, and exhibited a highly recyclable nature and a remarkably high TON and TOF.

We have also prepared Pd(OAc)₂ encapsulated in nanostructured hybrid silica with a well defined pyridine binding site via an ionic liquid templated sol-gel nanocasting technique for Heck and Sonogashira reactions.¹⁹²

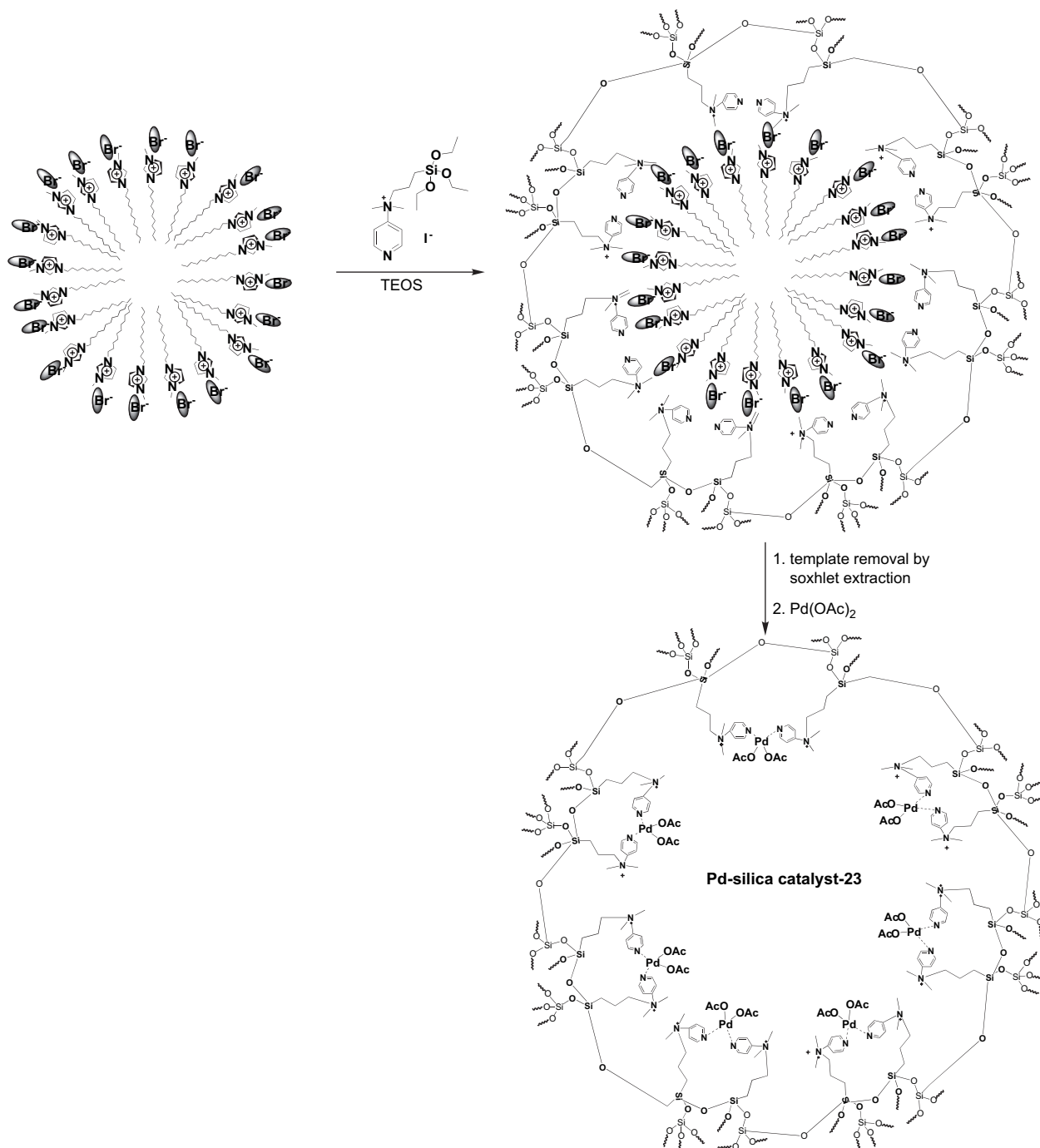
The organic sol-gel precursor **40** was synthesised by refluxing 4-*N,N*-dimethylaminopyridine and 3-iodopropyltriethoxysilane in a Schlenk tube, under an inert atmosphere. Notably, the reaction yields only the ammonium salt, keeping the pyridine site intact, which was efficiently utilised for complexation with Pd(OAc)₂ (Scheme 40).



Scheme 40. Synthesis of ionic sol-gel precursor.

In our group, a Heck catalyst was prepared by encapsulating Pd(OAc)₂ within nanostructured hybrid silica containing *N*-[3-(triethoxysilyl)propyl]-*N,N*-dimethyl-4-ammonium pyridine iodide (**40**) substructures, which are covalently bound to silica. In this process, the ionic liquid, *N*-methyl, *N*-dodecyl-imidazolium bromide was used as a template. The surfactant properties of this imidazolium ionic liquid, and the fact that this template has planar aromatic head groups as opposed to the bulky three-dimensional head group of the alkyltrimethylammonium template were exploited, in the synthesis of this nanostructured catalyst. For the synthesis of this material, *N*-[3-(triethoxysilyl)propyl]-*N,N*-dimethyl-4-ammonium pyridine iodide and TEOS were used as the sol-gel precursors. The formation of this nanostructured hybrid silica in the template-directed hydrolysis polycondensation procedure is induced by ionic interaction of the organic precursor, *N*-[3-(triethoxysilyl)propyl]-*N,N*-dimethyl-4-ammonium pyridine iodide with the micellar arrangement of the self-assembled ionic liquid template, *N*-methyl, *N*-dodecyl-imidazolium bromide, in aqueous solution followed by the encapsulation of palladium acetate. The schematic illustration of the synthesis of the Pd-silica catalyst-23 is presented in Scheme 41.

Electronic microscopy gave information about the morphology of the synthesised nanostructured Pd-silica catalyst-23 encapsulating Pd(OAc)₂. The SEM (scanning electronic microscopy) image shows agglomerates of particles with diameters in the range of several hundreds of nanometres up to a micrometre (Fig. 5). An X-ray fluorescence experiment with the material gave an Si/Pd molar ratio of 95.2/4.8. As the material was synthesised using a 9/1 ratio of TEOS and the



Scheme 41. Ionic liquid templated sol-gel nanocasting of Pd-silica catalyst-23.

ionic precursor, this result indicates a 2/1 ratio of the immobilised pyridine substructures and supported Pd species.

The TEM (transmission electronic microscopy) micrograph of some smaller particles (Fig. 6) clearly indicates a nanostructured material. The material appears of high regularity, as all of the observed particles show high degree of structuration.

A nitrogen adsorption-desorption experiment with the Pd-silica catalyst-23 (Fig. 7) resulted in a typical type IV isotherm. The catalyst exhibits 154 m²/g of surface area by BET measurement and a pore volume of 0.366 cm³/g.

The material was also characterised by solid-state MAS NMR spectroscopy. The ²⁹Si CP-MAS spectrum (Fig. 8) shows three characteristic signals and of these, the signals at –100 ppm and –109 ppm can be assigned to Q³ and Q⁴ sites, respectively, corresponding to SiO₄ substructures of different condensation degrees. The third signal at –66 ppm can be assigned to major T³ sites for RSiO₃ units possessing three siloxane bridges. In order to identify the organic functionalities attached to the silica support, ¹³C CP-MAS experiments were performed. The spectrum shows signals at 24, 40, 60, 108, 142 and 157 ppm, similar to the chemical shifts found in the liquid ¹³C NMR spectrum of the silylated organic precursor molecule (Fig. 9).

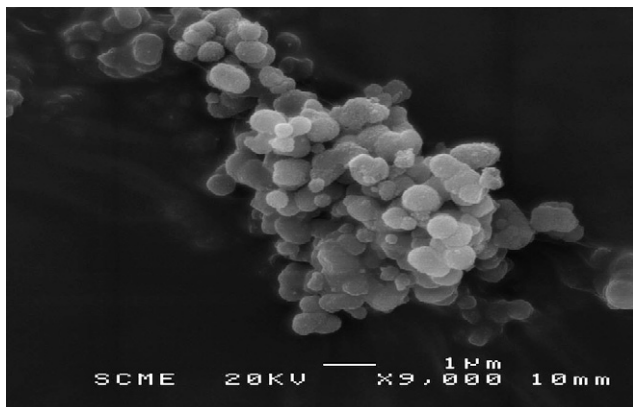


Figure 5. SEM image of Pd-silica catalyst-23.

Thus, the synthesised material incorporating palladium species is a mesoporous silica hybrid with a nanostructured morphology. The organic pyridine binding sites are firmly linked to the silica support. The material shows a narrow pore size distribution, indicating a high textural homogeneity of this catalyst. These features are important in view of the elaboration of materials showing high stability and long-lasting catalytic activity.

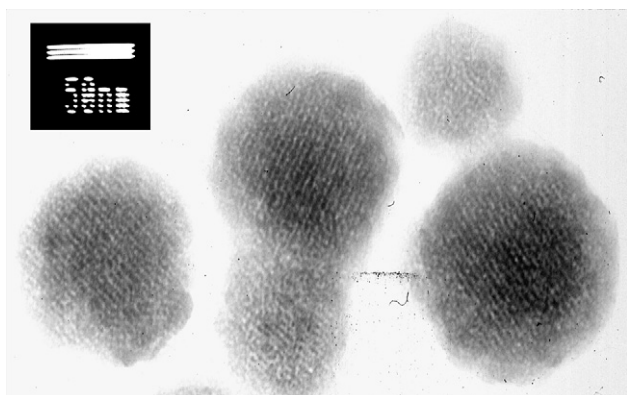


Figure 6. TEM image of Pd-silica catalyst-23.

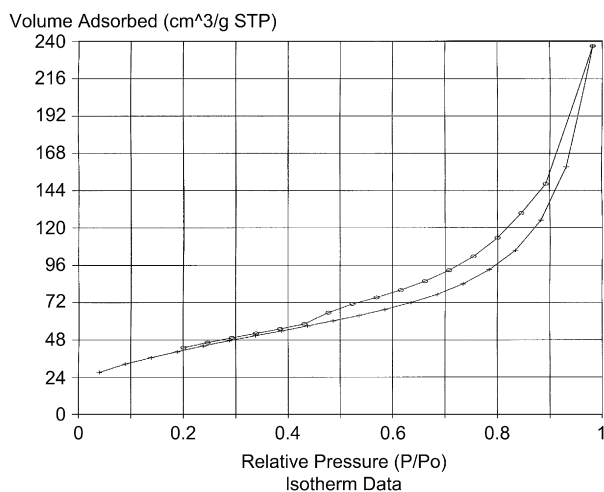


Figure 7. Nitrogen adsorption–desorption isotherm of Pd-silica catalyst-23.

The material acts as a pseudo-ligand by non-covalent anchoring between the pyridine sites and $\text{Pd}(\text{OAc})_2$ through metal–ligand interactions. This catalyst was used effectively for Heck and Sonogashira coupling reactions for at least five cycles with the same efficiency and without any catalyst deterioration or metal leaching (Scheme 42).

In this study, it was observed that $\text{Pd}(\text{OAc})_2$ encapsulated in *N*-[3-(triethoxysilyl)propyl]-*N,N*-dimethyl-4-ammonium pyridine modified nanostructured hybrid silica to form an efficient heterogeneous catalyst, offering the following advantages: (i) negligible Pd leaching due to non-covalent anchoring between the pyridine binding sites and $\text{Pd}(\text{OAc})_2$ and also due to the covalently bound ionic liquid protecting shell, (ii) simple reaction processing and easy recovery of catalyst, (iii) high efficiency and economic gain through the recovery and re-use of the catalyst and (iv) the nanostructured morphology allows high interaction between the substrates and catalyst, which increases the catalytic activity with good to excellent product yields.

9. Silica-supported Pd–TPPTS liquid-phase catalysts

The use of supported aqueous-phase catalyst is well known in the application of aqueous-phase organometallic catalysts using water-immiscible substrates.^{5,193} Its application at higher temperatures is rather limited, mainly due to deterioration of the water film. A similar concept can, however be applied using ethylene glycol as the catalyst phase.¹⁹⁴ $\text{PdCl}_2/\text{TPPTS}$ and $\text{Pd}(\text{OAc})_2/\text{TPPTS}$ catalysts (TPPTS: triphenylphosphine trisulfonate sodium salt) are known to work well under aqueous-phase intramolecular Heck cyclisation¹⁹⁵ at a very high catalyst concentration of 10 mol % of Pd. Tonks et al.¹⁹⁶ have demonstrated the application of ethylene glycol films using glass bead technology. They used freeze-dried glass beads coated with ethylene glycol containing a Pd–TPPTS catalyst and an organic phase containing olefin, aryl halide and triethylamine as the organic base. The major drawback of this system is the presence of triethylamine (one of the important catalyst components) in the organic phase. It is known that organic bases like triethylamine have a very high affinity for coordination with palladium,¹⁹⁷ as compared to inorganic bases such as sodium acetate. The organic bases may cause leaching in significant quantities, besides their main disadvantage of miscibility with the reactants and products. Beller et al.¹⁹⁸ have shown a biphasic Heck reaction using a Pd–TPPTS catalyst. Precipitation of Pd metal is, however a major limitation of this biphasic Pd–TPPTS catalyst system. Li et al.¹⁹⁹ have reported the use of metallic Pd supported on porous glass. They observed a lower conversion and selectivity in many cases, however the catalyst recycling data were not addressed. Arai et al.²⁰⁰ also developed a heterogeneous catalyst system using Pd–TPPTS immobilised in an ethylene glycol film supported on a silica and inorganic base like potassium acetate (Pd-silica catalyst-24) (Scheme 43). This catalyst has been applied to Heck reactions in organic solvents. The activity of this catalyst is comparable to that of the active homogeneous catalysts reported in the literature.

Arai et al. also examined the effects of preparation variables for palladium-based supported liquid-phase catalyst (SLPC)

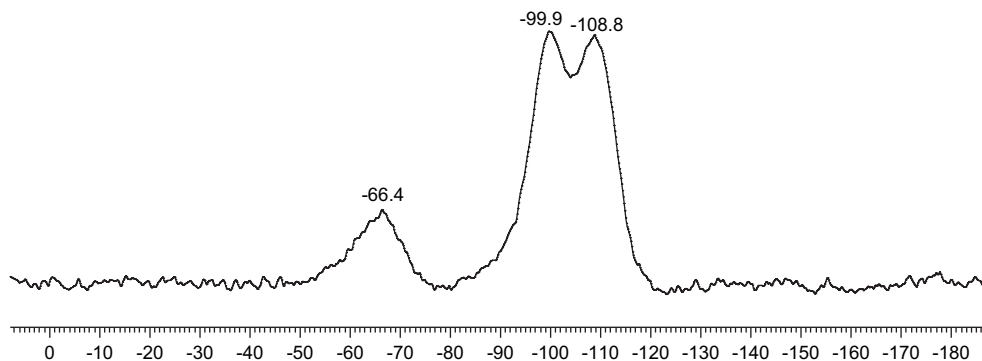


Figure 8. ^{29}Si CP-MAS spectrum of Pd-silica catalyst-23.

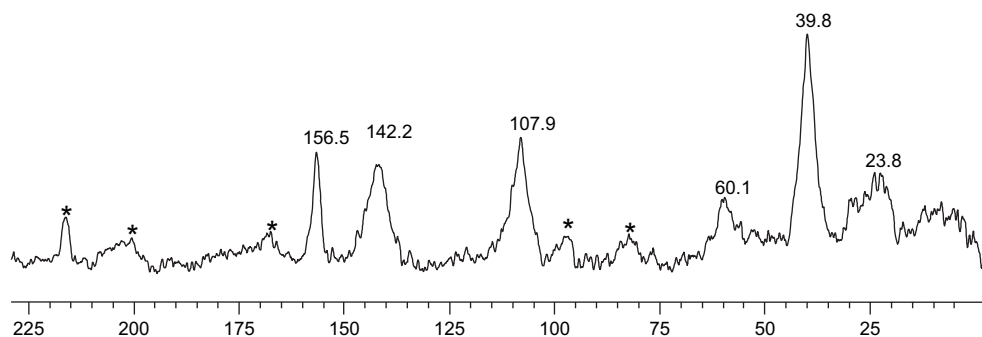
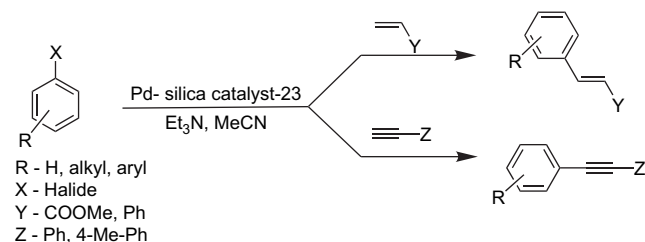


Figure 9. ^{13}C CP-MAS spectrum of Pd-silica catalyst-23.

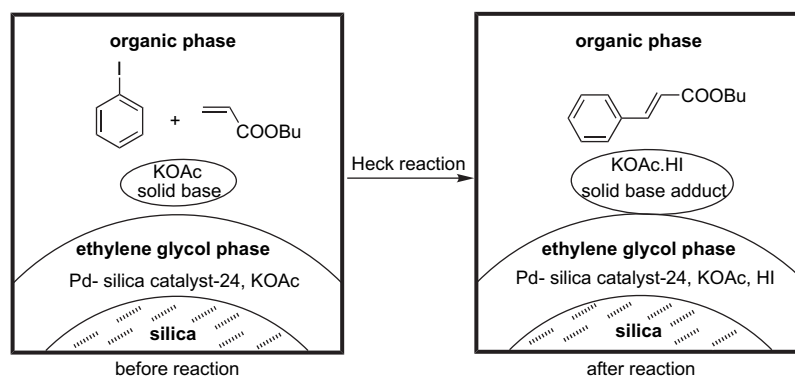
samples using Heck coupling as a model reaction.²⁰¹ It was observed that the rate of reaction depends on the concentration of the Pd–TPPTS complexes in the dispersed phase of ethylene glycol and changes little with the quantity of the dispersed liquid phase used. The SLPC sample can be re-



Scheme 42. Heck and Sonogashira reactions using Pd-silica catalyst-23.

used and the rate of reaction is promoted during the repeated runs, due to an effect of the Et_3NHI formed and accumulating in the dispersed phase.

These co-workers also studied effects of the reaction conditions and various amines on the reaction rate of the Heck reaction with a silica-supported Pd–TPPTS liquid-phase catalyst²⁰² and found that the reaction rate depends on the concentration of the Pd–TPPTS complex in the supported phase, and not on the total quantity of Pd–TPPTS. The rate increases linearly with the PhI concentration. The reaction rate also increases linearly with the concentrations of butyl acrylate and triethylamine (Et_3N), when these are low. A plateau and a maximum of the rate are, however, seen with a further increase in the concentrations of butyl acrylate and Et_3N , respectively. The reaction rate increases



Scheme 43. Heck reaction using Pd-silica catalyst-24.

with the total concentration of PhI, butyl acrylate and Et₃N by an order of twofold. The dependence of the reaction rate on these concentrations with a palladium–triphenylphosphine (Pd–TPP) homogeneous catalyst is quite similar to that with SLPC. The reaction rate also depends on the type of amine used. Tributylamine (Bu₃N) gives a faster reaction than Et₃N with both SLPC and Pd–TPP. Such an effect of trihexylamine (Hex₃N) is, however seen only with Pd–TPP. In the SLPC system, Hex₃N gives almost the same rate as that with Et₃N. The promotive effect of recycle use of the SLPC sample is also affected by the type of amine.

10. Pd leaching

Homogeneous and heterogeneous catalysts offer their own distinct advantages. Heterogeneous catalysts have the advantage that, at the end of the reaction, the catalyst can be removed by simple filtration. In principle, the product is uncontaminated with a transition metal or ligand and allows the catalyst to be recycled into the next reaction. While the distinction between homogeneous and heterogeneous catalysis seems well defined, in many cases there may be leaching of the transition metal into solution. In these instances, the question that always remains is whether the catalytic activity resides with the leached metal.²⁰³ In other situations, it is unclear whether a *release and capture* of the transition-metal catalyst has occurred.

The catalytic activity is influenced by the nature of the support and the dispersion of the Pd. These traditionally supported Pd catalysts can leach Pd under the reaction conditions and deactivate from the aggregation of Pd nanoparticles undergoing a Pd release/redeposit process. In an effort to reduce the leaching of Pd into solution, supports functionalised with P-, N-, or S-containing ligands have been used to anchor the Pd. A recent report by Yu et al. demonstrated conclusively that both silica- and polymer-immobilised Pd–SCS pincer complexes were only precursors of a leached solution-phase Pd species, which functioned as the active species in the Heck reaction.¹²⁹ The issue with solid Pd catalysts for the Heck reaction, i.e., whether the catalysis is truly heterogeneous, is still unresolved. The reason that many researchers claim their catalysts to be recyclable and heterogeneous is a negligible loss in the catalytic activity or Pd loading after re-use. The Heck reaction can, however be easily catalysed by only a 5–10 ppm level of Pd in solution.²⁰⁴ Thus, a high activity can still be obtained after re-use of a solid Pd catalyst if the support contains a substantial amount of the unleached metal. The supported catalyst will continue to function as a reservoir of Pd that can be released at very low levels into solution. The general methods to test for the presence or absence of leached soluble Pd in the reaction solution are a hot filtration test or elemental analysis of Pd in the solution. In some cases, however the leached soluble Pd can redeposit back onto the support after completion of the reaction.⁹²

In the absence of truly effective supported catalysts, a variety of scavengers for Pd have been developed to treat the solution or substrate after the reaction. These are summarised in a recent comprehensive review by Prasad et al.²⁰⁵ and include three basic approaches: (i) precipitation from solution

after complexation by a ligand, (ii) adsorption onto a polymeric support, which can be removed by filtration or (iii) removal of the product while keeping Pd dissolved in solution. As an example, palladium can be precipitated from solution using 2,4,6-trimercapto-S-triazine (TMT).²⁰⁶ Treatment with unfunctionalised adsorbents such as charcoal is sometimes effective, but can also lead to significant losses of products, which are also adsorbed. Organic polymers functionalised with thiols such as MPTMT (mesoporous polystyrene-bound TMT) and related species are commercially available, but require long reaction times in excess of 24 h and large excesses of reagent to effectively remove Pd from solution.

10.1. Poisoning test

10.1.1. Pyridine as a poison. Pyridines are known to bind strongly to Pd(II). Yu et al.¹²⁹ successfully used insoluble poly(4-vinylpyridine) (2% cross-linked) (PVPy) as a Pd(II) trap to confirm the presence of leached, soluble Pd from an organometallic Pd complex anchored to silica. Davis et al.²⁰³ used both soluble pyridine and insoluble PVPy to differentiate between the solid Pd phase and leached, soluble Pd during the Heck reaction catalysed by silica-supported Pd. In this study, four different supported Pd catalysts, amorphous silica-supported Pd (Pd–SiO₂), zeolite Y ion exchanged with [Pd(NH₃)₄]²⁺ (Pd-Y), mercapto- and amine-functionalised amorphous silica with immobilised Pd (Pd-SH-SiO₂ and Pd-NH-SiO₂) and mercapto-functionalised SBA-15 with immobilised Pd (Pd-SH-SBA-15), were tested for Pd leaching. As a control, soluble Pd acetate was used as a catalyst in the reaction. Pyridine or PVPy was added along with all of the other reagents before starting the reaction. The results showed that pyridine addition with a mole ratio of 700:1 (pyridine to Pd) did not deactivate the catalyst, since iodobenzene conversion after 1 h was almost unchanged, compared to the standard reaction. These results are consistent with those reported by Klingelhofer et al., who studied the coupling of styrene with 4-bromoacetophenone.²⁰⁷ In contrast, a reaction mixture containing the same molar ratio of PVPy to Pd (700:1) resulted in only a 6% iodobenzene conversion after 1.5 h and remained at this low level, even after 2 h. Since addition of PVPy deactivated the homogeneous catalyst, insoluble PVPy can be used as a trap for soluble Pd, thus indicating the presence of a leached Pd species from a supported Pd catalyst during the Heck reaction. Similar to the results with Pd acetate, addition of pyridine did not deactivate the catalyst, whereas the addition of PVPy nearly quenched the reaction in the presence of Pd–SiO₂, indicating that the catalytic activity of Pd–SiO₂ was mainly from the soluble Pd leached from the solid catalyst. The degree of Pd leaching was also determined in the course of the reaction by 5 wt % Pd–SiO₂ (catalyst loading 1.0 mol % of Pd relative to iodobenzene), and approximately 2 ml of clear filtrate was removed after two different time intervals. The concentration of leached Pd in solution was found to be 12 and 4.5 ppm after 10 and 60 min, respectively. A decrease of Pd concentration in solution with time is consistent with the observation by Heidenreich et al.⁹⁴ The trace analysis of Pd in solution and the deactivation of Pd–SiO₂ by PVPy suggest that the Pd gets released from the support and that the soluble Pd might be responsible for most of the activity in Heck catalysis.

10.1.2. Mercury as a poison. The ability of Hg(0) to poison metal-particle heterogeneous catalysts, by amalgamating the metal or adsorbing on the metal surface, has been known for many years. Hg(0) is especially effective in poisoning Pt, Pd, and Ni metals by forming an amalgam.²⁰⁸ Hg(0) is, however, not expected to have a poisoning effect on molecular homogeneous organometallic complexes containing metals in high oxidation states that are tightly bound by protective ligands, especially pincer complexes that utilise a hypothetical Pd(II)–Pd(IV) cycle. When a Heck reaction is performed in the presence of excess Hg(0) using a precatalyst, no activity is observed, even after 2 h. This provides evidence that the SCS-pincer-type Pd(II) precatalyst decomposes under the reaction conditions to form soluble Pd(0) species and that Hg(0) interactions with these Pd(0) moieties completely kill the reaction. In a similar experiment, in the presence of excess Hg(0), the homogeneous SCS-pincer Pd(II) complex also showed no Heck reactivity. This is consistent with a breakdown of pincer ligand–Pd bonds to liberate Pd(0) species.¹²⁹

10.2. Hot filtration test

To determine whether the catalyst is actually functioning in a heterogeneous manner, or whether it is merely a reservoir for more active soluble forms of Pd, various heterogeneity tests were performed by Crudden et al.¹⁴⁸ First, the reaction was carried out in the presence of 0.5 ppm of Pd(OAc)₂, because traces of Pd have been reported by Leadbeater to have a high catalytic activity.²⁰⁹ After 8 h at 80 °C under otherwise standard conditions, Crudden and co-workers found less than 5% conversion. In addition, they examined¹⁴⁸ the leaching of Pd at various points in the reaction. With the SBA-15-SH-modified materials, the same level of Pd at different points in the reaction was observed, which is inconsistent with a mechanism in which the substrate is removing the Pd from the support and the reaction is occurring in solution. A hot-filtration test was also performed,²¹⁰ which entails filtering a portion of the solution after the reaction is initiated, and before the substrate is consumed. After filtration, both

portions were heated for a total reaction time of 8 h and the conversion in both samples was determined.

Crudden et al. have also carried out this hot filtration test to check the heterogeneity of the developed catalyst.¹⁴⁸ The reaction and filtration were carried out in DMF in a glove box to prevent oxidation of the catalyst. After 3 h, the reaction was split at a conversion of 28%. After an additional 5 h, the portion containing the suspended catalyst had proceeded to 97% conversion, while the catalyst-free portion had reacted by only an additional 1%.

10.3. Three-phase test

The three-phase test is a simple unambiguous test to determine the presence of a homogeneous catalyst and demonstrate its application in three prototypical reactions. Not only does this method clarify the phase of the catalytically active species, but it also allows additional mechanistic information to be obtained regarding the system.

This test, developed by Rebek and co-workers, is considered to be definitive for the presence of catalytically active homogeneous metal species.^{211,212} Corma,^{213,214} Davies²¹⁵ and others have employed the test in a variety of systems. The test consists of covalently immobilising one of the reaction partners, e.g., aryl halide, and examining its reaction with a soluble reagent and the catalyst, supported on a third phase. If the catalyst remains immobilised, it will be incapable of accessing the supported aryl halide, but, if homogeneous Pd is released, the supported substrate can then be converted into the product. In addition, it is critical to add a soluble aryl halide to the reaction to ensure that an active catalyst is present, and also to provide a more correct mimicry of the reaction conditions.

Davies et al.²¹⁵ showed that a supported aryl iodide (**41**) (Fig. 10) was completely inactive in the Pd/C-catalysed methoxycarbonylation reaction, unless a soluble aryl iodide was added, in which case complete conversion of the immobilised substrate was observed.

Aryl halide **42** and butyl acrylate promoted by Pd/alumina (2 mol %) proceeded to give the cinnamate **44** in 98% yield (Scheme 44). Iodobenzene and the iodoamide **43** coupled with similar efficiency.

Performing the Heck reaction in the presence of resin **41** led to the quantitative formation of cinnamate **45** following TFA cleavage. Control experiments indicated that, in the absence of the aryl halide, low conversions of **41** were observed and the rate of reaction increased with the sodium acetate charge (2–5 equiv). The conversion and rate of reaction of **41** were

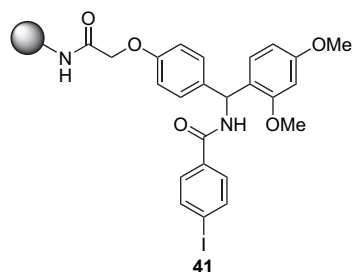
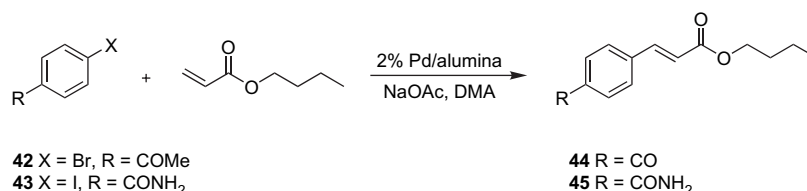


Figure 10. Resin-supported aryl iodide.



Scheme 44. Heck reaction for three-phase test.

greatly enhanced by the presence of both the aryl halide **42** and sodium acetate, i.e., they act co-operatively. Surface oxidative addition occurs and desorption of the palladium(II) species is presumably accelerated by the formation of ArPd-Br(OAc)_n or ArPd(OAc)_n, which are free to enter a conventional solution-phase reaction. These results firmly establish the involvement of a homogeneous catalyst. The resin may, however, serve as a convenient catalyst precursor for the release of palladium and acts as a scavenger for palladium capture at the end of the reactions.

11. Conclusions

The Heck reaction is among the most important and widely used reactions for the formation of carbon–carbon bonds, which allows the arylation, alkylation or vinylation of various alkenes through their reaction with aryl, vinyl, benzyl or allyl halides, acetates or triflates in the presence of palladium and a suitable base in a single step under mild conditions. For the industrial application of the Heck reaction, it is important to establish good strategies for the catalyst–product separation and the catalyst recycling and this has been achieved by various heterogeneous catalysts. The heterogeneous catalysts include silica-supported metal catalysts, zeolite-encapsulated catalysts, colloidal nanoparticles and ionic liquid supported metal catalysts. Silica-supported catalysts are, however, advantageous over the other catalysts, since they show some excellent properties, such as high stability (chemical and thermal), good accessibility, and also due to the fact that organic groups can be robustly anchored to the surface to provide catalytic centres.

Acknowledgements

V.P. thanks Prof. J.J.E. Moreau and Dr. Peter Hesemann for their guidance and valuable suggestions. Thanks are also due to the ‘Direction de la recherche’, French Government, for a postdoctoral fellowship.

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