Recovery and reuse of ionic liquids and palladium catalyst for Suzuki reactions using organic solvent nanofiltration

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The separation, post-reaction, of ionic liquids and catalysts from reaction products is an unresolved challenge in the application of ionic liquids to organometallic catalysis. This paper addresses this challenge using organic solvent nanofiltration technology. Suzuki reactions were carried out in a homogeneous solution, comprising 50 : 50 wt% ethyl acetate and ionic liquid. The post reaction mixture was diluted further with ethyl acetate and then separated by nanofiltration into a permeate fraction and a retained (retentate) fraction. The product was recovered in the nanofiltration permeate, while the ionic liquid and palladium catalyst were retained by the membrane and recycled into subsequent consecutive reactions. Thus, the organic solvent nanofiltration was able to separate the Suzuki reaction product from both catalyst and ionic liquid. Three ionic liquids were tested: cocosalkyl pentaethoxi methyl ammonium methosulfate (ECOENG™500), tetrabutylammonium bromide (TBAB) and trihexyl(tetradecyl)phosphonium chloride (CyPhos®101). All the ionic liquids screened showed positive effects on the catalytic stability, significantly reducing the formation of palladium black and providing high reaction yields over consecutive recycles. The best performance was observed for the CyPhos®101 system. Additional investigations employing this ionic liquid showed that the reaction–recycle process can be successfully performed at lower catalyst–substrate ratios, leading to higher catalyst turnover numbers.

Introduction

The properties of ionic liquids (ILs) can be engineered through ion selection, and this flexibility has earned them a reputation as "designer" solvents.[1–8] ILs are used in a continually evolving range of applications, including cross-coupling reactions where the benefits of these highly polar yet non-coordinating solvents has been demonstrated.[9–12] An example of such a reaction is the Suzuki coupling, a key step in the synthesis of active pharmaceutical ingredients,[13,14] where ILs have provided enhanced catalytic activity and stability.[15,16] However, an unresolved challenge is the efficient separation of IL from products in post-reaction mixtures. Separation of Suzuki reaction products from IL and homogeneous transition metal catalyst (TMC) *via* solvent extraction is the conventional choice[9–11] for obtaining IL (and catalyst in some cases) in a recyclable form (see Fig. 1a). However, while solvent extraction is suitable for separation of apolar products, its use in separation of polar products is more problematic. For the latter case, a moderately polar extracting organic solvent (OS) is required, but since ILs tend to have significant partition coefficients into polar solvents, or are completely miscible with them, this can result in loss of IL to the product stream.

We propose that organic solvent nanofiltration (OSN) can provide a separation solution which reduces these problematic losses. In this context, we envisage two schemes for the use of OSN. In systems in which the IL and the moderately polar extracting solvent form a biphasic mixture, a significant amount of IL can partition into the organic solvent phase. The first scheme involves (see Fig. 1b) separating the phases, and then applying OSN to the organic solvent phase to separate the product from the IL. The IL can be retained by the membrane, and then recycled to the reaction system. The second scheme, investigated in this paper, (see Fig. 1c) dispenses with the need for an intermediate solvent extraction. The reaction is carried out in a homogeneous solution of IL and organic solvent. The post reaction mixture is subjected to OSN, resulting in a permeate stream containing solvent and product, and a retentate stream containing solvent, TMC and IL.

This study extends our previous work using single-phase mixtures of IL with organic solvents for Suzuki couplings.[17] We found that pure ILs can lower reaction rates due to unfavourable heat and mass transfer characteristics arising from their high viscosities (*e.g.* ECOENG™500 displays 3150 cP at 20 °C[17]). Using 50 : 50 wt% mixtures of organic solvent and miscible ILs avoided the problems associated with these high viscosities, while maintaining the beneficial effects of IL on the reaction. Crucially, this means that IL can be recycled for use in subsequent reactions as a single phase mixture with organic solvent, as opposed to in the form of pure IL. In these cases, the scheme shown in Fig. 1c is directly applicable.

The nanofiltration of organic solvents has been made possible by the development of solvent stable nanofiltration

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† MWCO of the membranes used here was obtained from a plot of the rejections of a series of n-alkanes dissolved at 2 wt% in toluene, *versus* alkane molecular weight. MWCO is defined as the molecular weight (MW) for which rejection by the membrane is 90%.

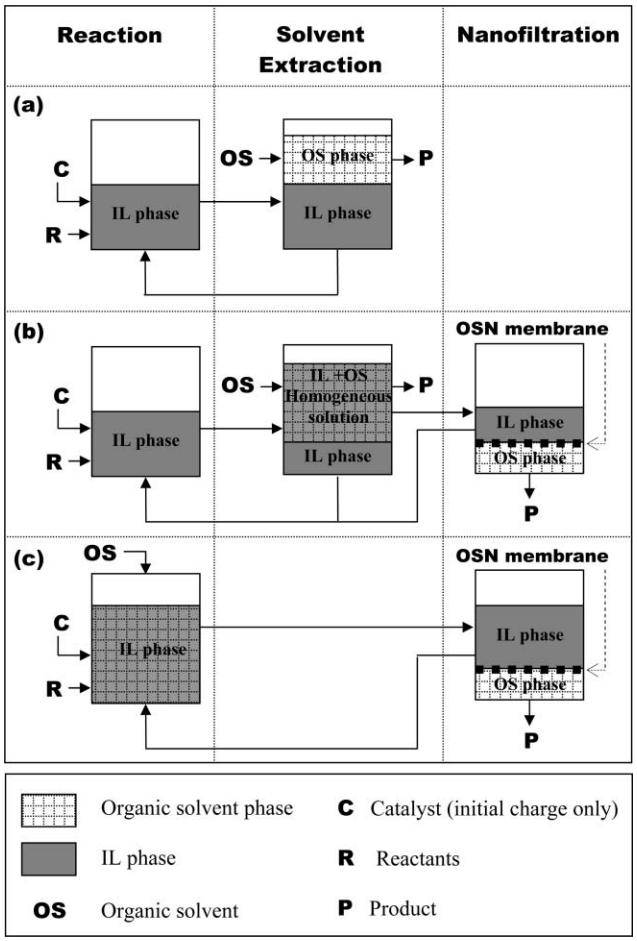


Fig. 1 IL/TMC recycle schemes for coupling reactions: (a) conventional product isolation *via* solvent extraction, (b) OSN used with a bi-phasic IL/organic system, and (c) OSN used with a single phase IL–organic solvent system.

membranes.[18] These membranes have molecular weight cut offs (MWCOs)† in the range 200–1000 g mol^{-1}. Separation of large molecules (*i.e.* large IL and TMC) from smaller sized molecules within this range (*i.e.* small reaction products) has been reported previously.[19,20] Cross-flow nanofiltration of synthetic post reaction mixtures has demonstrated high IL rejections‡, R^i > 95% for ECOENG™500 and CyPhos®101.[21]

In this study, for the first time, we combine a reaction in a single phase IL–organic solvent medium with OSN to implement consecutive Suzuki reactions, using only a single initial charge of IL and TMC. We also investigate decreasing TMC loading, in order to minimise palladium contamination levels in the product stream.

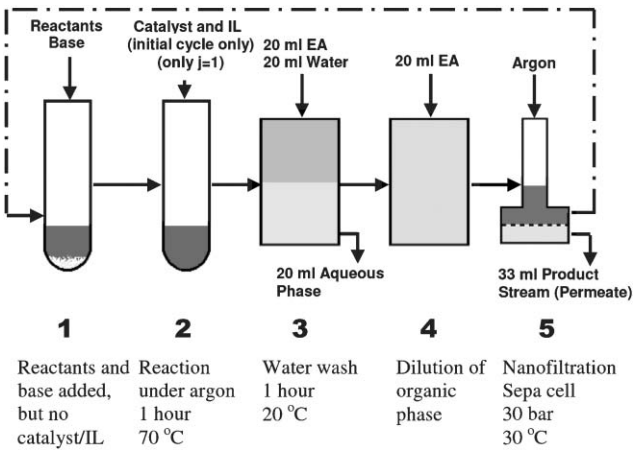


Fig. 3 Catalyst and IL recycle process, showing the different stages (1–5) involved between reaction and nanofiltration.

Results and discussion

IL Screening

The following ILs were used in 50 : 50 wt% homogeneous mixtures with ethyl acetate: tetrabutylammonium bromide (TBAB), ECOENG™500 and CyPhos®101. The model reaction selected for this work (Fig. 2) was the formation of 4-acetyl-biphenyl (ABP) by the Suzuki coupling between 4-bromoacetophenone (BrAP) and phenylboronic acid. Tris(dibenzylideneacetone)dipalladium chloroform complex ($Pd_2(dba)_3$–CH_3) was used as the TMC, BrAP was added as the limiting reactant and reaction time was 1 hour in all the experiments. Reactions were also carried out in pure ethyl acetate to act as a control. ILs were selected based on achieving satisfactory yields for the Suzuki coupling as well as high R^{IL} (>95%) with STARMEM™ 122§, the OSN membrane used throughout this work.[17,21]

The product recovery and IL recycle process used in this work can be seen in Fig. 3. After the reaction (stage 2), an aqueous wash stage was used to remove solid water-soluble by-products. The post reaction mixture was then filtered,

‡ $R^i = \left(1 - \frac{C^i_{permeate}}{C^i_{retentate}}\right) \times 100\%$ where C is concentration.

§ STARMEM is a trademark of W.R. Grace and co.

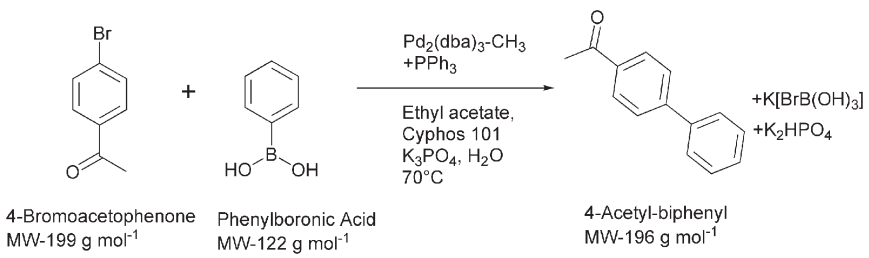


Fig. 2 Suzuki reaction forming 4-acetyl-biphenyl.

where the OSN membrane retained the IL and TMC for recycling into following reactions, while the product and ethyl acetate permeated through.

This paper is focused on the recycle process as a whole, so the results are reported as process yields (Y), which are defined for each cycle (j) as:

$$Y_{j,\ \text{process}}(\%) = \left(\frac{\text{ABP}_{j,\ \text{stage 5 permeate}}(\text{mol})}{\text{BrAP}_{j,\ \text{fed to stage 1}}(\text{mol})}\right) \times 100\% \qquad (1)$$

It is worth noting that the process yield (see eqn (1)) defined in this paper should be distinguished from the reaction yield (see eqn (2)), which does not take the process workup into account. In the process (see Fig. 3), the retentate from stage 5 is recycled to stage 1 of the following cycle. This retentate contains a small amount of the product (ABP) and unreacted BrAP, and so the reaction yield for each cycle (j) is calculated as:

$$Y_{j,\ \text{reaction}}(\%) = \left(\frac{\text{ABP}_{j,\ \text{fed to stage 5}} - \text{ABP}_{j-1,\ \text{stage 5 retentate}}(\text{mol})}{\text{BrAP}_{j,\ \text{fed to stage 1}} + \text{BrAP}_{j-1,\ \text{stage 5 retentate}}(\text{mol})}\right) \times 100\% \qquad (2)$$

Fig. 4 shows the process yield (see eqn (1)) plotted against the number of process cycles for each solvent system. The first reaction for the pure ethyl acetate and the various ethyl acetate–IL mixtures shows a surprisingly constant yield of 75–85%. This is consistent with our previously reported work.[17] In subsequent reactions the process yields for all but the ethyl acetate–CyPhos®101 system fall rapidly. The ethyl acetate–CyPhos®101 system maintains higher process yields (>70%) over a larger number of cycles than any of the other solvent systems screened. This indicates that CyPhos®101 provides an extraordinary level of catalyst protection compared to the other ILs, although ethyl acetate–EE500 and ethyl acetate–TBAB still maintain moderately higher yields than the pure ethyl acetate system. Fig. 4 also shows that process yields increase in all systems over cycles 2–4. This is explained by the initial accumulation of ABP within the process due to ABP in the retentate. For example, in the ethyl acetate–CyPhos®101 system, the yield increases over the first cycles and then reaches

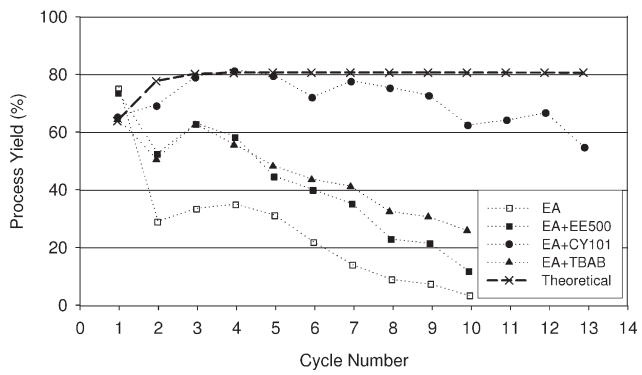


Fig. 4 Process yields from using recycled catalyst–IL, for pure ethyl acetate (EA), EA–ECOENG™500 (EE500), EA–CyPhos®101 (CY101) and EA–tetrabutylammonium bromide (TBAB) systems (all IL systems 1 : 1 wt% IL : EA). All experiments initially had 5.0 mol% catalyst loading.

a steady value, equal to the reaction yield, at the 3rd cycle. Finally, it starts to decline slowly after the 5th cycle. During this period it is evident that the OSN workup recovers all the ABP after the initial accumulation in the retentate fraction.

To understand this behaviour, the theoretical process yield was iteratively calculated assuming (a) consistent reaction yields of 80%; (b) no formation of side product, which means process yield and process conversion are equal; (c) $R^{\text{BrAP}} = 0$ and $R^{\text{ABP}} = 0$; and (d) that the ratio between the volume of feed solution and retentate in the filtration ($V_{j-1,\ \text{retentate}}/V_{j-1,\ \text{feed}}$) was 0.175 (see eqn (3)). Obviously, there is nothing recycled into stage 1 for the first cycle ($j = 1$) *i.e.* $\text{BrAP}_{j-1\ =\ 0,\ \text{stage 5 retentate}}$ and $\text{ABP}_{j-1\ =\ 0,\ \text{stage 5 retentate}}$ equal zero moles.

$$Y_{j,\ \text{calculated process}}(\%) = \left(1 - \frac{V_{j,\ \text{stage 5 retentate}}}{V_{j,\ \text{fed to stage 5}}}\right) \times \frac{\text{ABP}_{j,\ \text{fed to stage 5}}(\text{mol})}{\text{BrAP}_{j,\ \text{fed to stage 1}}(\text{mol})} \times 100\% \qquad (3)$$

where,

$$\text{ABP}_{j,\ \text{fed to stage 5}}(\text{mol}) = \frac{V_{j-1,\ \text{stage 5 retentate}}}{V_{j-1,\ \text{fed to stage 5}}} \times \text{ABP}_{j-1,\ \text{fed to stage 5}}(\text{mol}) + \frac{Y_{\text{reaction}}(\%)}{100} \times \left(\text{BrAP}_{j,\ \text{fed to stage 1}}(\text{mol}) + \text{BrAP}_{j-1,\ \text{stage 5 retentate}}(\text{mol})\right) \qquad (3a)$$

$$\text{BrAP}_{j-1,\ \text{stage 5 retentate}}(\text{mol}) = \frac{V_{j-1,\ \text{stage 5 retentate}}}{V_{j-1,\ \text{fed to stage 5}}} \times \left[\left(1 - \frac{Y_{\text{reaction}}(\%)}{100}\right) \times \left(\text{BrAP}_{j-1,\ \text{fed to stage 2}}(\text{mol})\right)\right] \qquad (3b)$$

The theoretical process yield starts at less than 70%, reaches a value slightly above the reaction yield by the 4th cycle, and then gradually declines over subsequent reactions. This is because the ABP product recycled in the retentate from the first reactions gradually works its way out of the system, along with the ABP formed in each consecutive reaction. The theoretical and actual process yields deviate. There are two main explanations for this decline in process yields with increasing reaction–filtration cycles, and both are related to a decreasing reaction yield resulting from the loss of active palladium catalyst, which is only added to the first cycle. The first explanation is the physical loss of catalyst from the process *via* sampling of the nanofiltration feed (in this process, 2.5% of catalyst present in each cycle is lost). Some catalyst is also lost through the aqueous phase of the water wash.

The second explanation for the process yield decline arises from catalyst instability and the consequent decrease in its activity. One possible scenario is that the catalyst decomposes into smaller fragments, which can penetrate through the OSN membrane (stage 5, Fig. 3). An attempt was made to retain the palladium remaining in the permeate stream by using a second filtration stage. However, it was unsuccessful and this suggests that the palladium may pass through the membrane in a degraded form, which has a reduced size compared to its original catalytic structure.

This degraded form could be related to the formation of catalytically inactive palladium black precipitate. This

Table 1 Percentage of palladium initially added to system appearing as palladium black in different solvent systems, totalled over all the cycles

Solvent system	Catalyst loading (mol%)	Pd appearing as black precipitate (%)
EA	5	73.4
EA–CY101	5	24.8
EA–CY101	0.9	15.9

precipitate is a sign of palladium catalyst deactivation and this is thought to arise from agglomeration of palladium intermediates.[22] In our system, significant palladium black was removed along with the aqueous phase leaving stage 3 (see Fig. 3) and was quantified by ICP analysis after dissolution with aqua regia. Palladium black was formed in all the solvent systems, indicating that the ILs screened could not completely prevent the deactivation of the catalyst. However, Table 1 shows 73% of palladium from the catalyst is lost as palladium black in the ethyl acetate system. This is almost three times the observed loss in the ethyl acetate–CyPhos®101 system, illustrating the significant degree of catalyst stabilisation provided by CyPhos®101. The enhancement of stability may arise from a mechanism which involves a monomolecular layer of IL[23] surrounding the palladium core and preventing the agglomeration of colloidal palladium.

It is also interesting to note that individual analysis of each cycle shows the majority of palladium black is formed during the first two cycles. For example, 66% of the initial amount of palladium was lost in the first cycle in the pure ethyl acetate system. An average of 0.08% was lost in each cycle from the 3rd cycle onwards. This palladium loss is clearly related to the sharp decline in the process yield (see Fig. 4) for the first two cycles of the ethyl acetate system.

The water wash (stage 3, Fig. 3) was introduced to remove the water soluble by-products. Water soluble potassium ions, introduced to the process by the addition of K_3PO_4, are removed in this stage. Quantitative analysis of the amount of potassium in the water phase showed that consistently 70–80% of the potassium added is removed in the water wash of the organic phase over all the cycles. The water wash also provides a relatively neutral pH environment for the nanofiltration membrane by extracting the base from the organic phase.

Quantitative analysis of boron has also been performed. The amount of boron in the water phase was compared with the amount of boron in the limiting reactant BrAP that forms the by-product. This mass balance closed within 90%, showing that the by-product, $K[BrB(OH)_3]$, is removed from the process through the water wash. This avoids a build up of solid material within the process that might foul the membrane surface.

In the model reaction, BrAP is employed as the limiting reactant. From the number of moles of BrAP consumed in the reaction, an equivalent number of moles of product ABP should be generated, assuming no undesirable side reactions. This is expressed through the correlation between process yield and process conversion, see eqn (4). In Fig. 5, the correlation between them suggests that process conversion is consistently 10–20% higher than process yield for all the

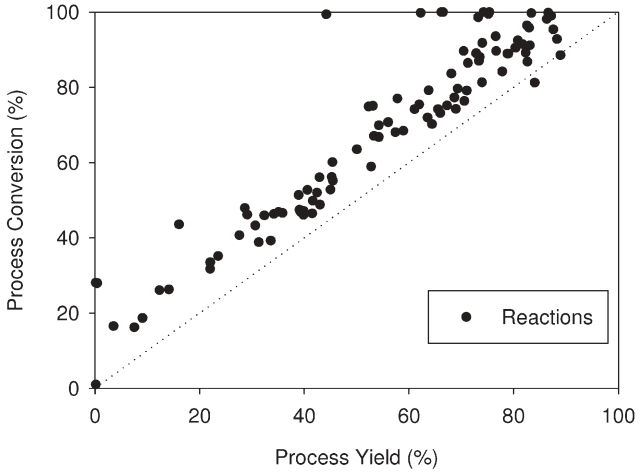


Fig. 5 Process yield *vs* process conversion (see eqns (2) and (5)).

solvent systems. This implies that around 80–90% of the reacted BrAP forms ABP, while the remaining 10–20% is consumed by the formation of unwanted side products. Process conversion (X) is defined as:

$$X_{j,\text{process}}(\%) = \left(1 - \frac{\text{BrAP}_{j,\text{ stage 5 permeate}}(\text{mol})}{\text{BrAP}_{j,\text{ fed to stage 1}}(\text{mol})}\right) \times 100\% \quad (4)$$

Palladium contamination

Fig. 6 shows the levels of palladium per unit mass product in the filtration permeate stream. This is a key variable in terms of pharmaceutical quality control and consumer safety, where a typical range of 2–10 mg palladium per kg of product[24] is required. Overall, although the palladium levels have been greatly reduced by the nanofiltration stage (*e.g.* by 79 times for the 1st CyPhos®101 cycle), the palladium levels in the permeate streams are still unacceptable for a pharmaceutical grade product and thus further reduction is desirable.

The results from the metal analysis show that the amount of metal in the permeate stream in all solvent systems follow a similar pattern shown in Fig. 6; initially decreasing and then appearing to spike after cycle 5. No plausible explanation can be offered for this unsystematic spiking. As suggested by the two stage filtration results described above, the palladium

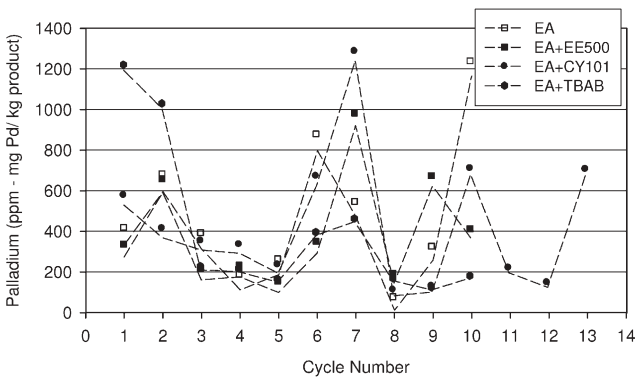


Fig. 6 Palladium loading in the nanofiltration permeate stream.

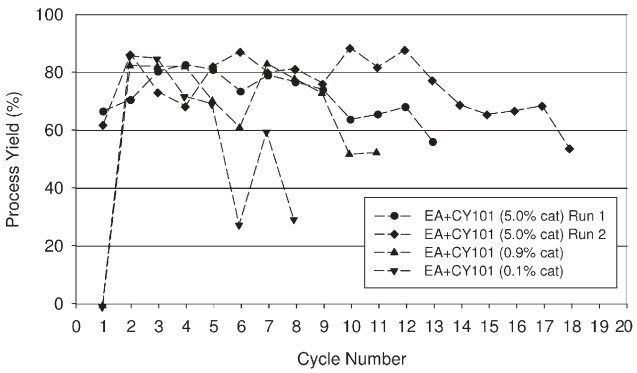
species may be in a degraded form. Nair *et al.*[19] reported loss of the membrane selectivity for recycling palladium catalyst in Heck reactions over consecutive reactions, and speculated this was due to the degradation of catalyst into nanoparticles. A similar phenomenon could take place in the experiments reported here, with the spiking observed in the product stream of this system corresponding to the cycles in which, for some reason, more nanoparticles leave the system *via* the OSN permeation.

Catalyst loading reduction

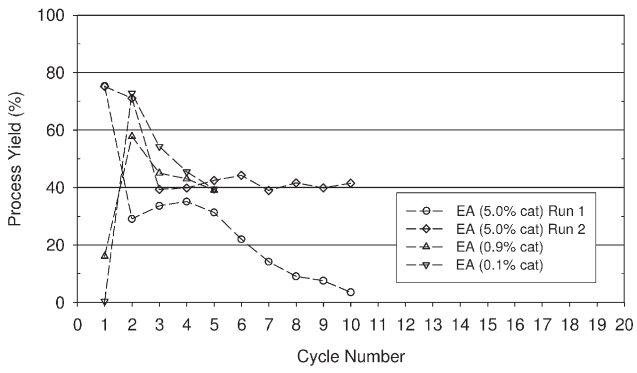
One obvious approach to reduce the palladium in the permeate is by using less initial catalyst for the reactions. In this study the catalyst loading was reduced from 5.0 mol% to 0.9 mol%, and then down to 0.1 mol% for reactions performed in ethyl acetate and ethyl acetate–CyPhos®101 systems. The process yields (see Fig. 7) also drop for the low catalyst loading, as one would expect. Palladium black was also observed for lower catalyst loadings (Table 1). Turn Over Number (TON) is calculated as:

$$\mathrm{TON}_j = \frac{\sum_{k=1}^{k=j} \mathrm{ABP}_{k,\ \text{stage 5 permeate}}(\mathrm{mol})}{\mathrm{TMC}^{\text{only initial charge}}_{j=1,\ \text{fed to stage 2}}(\mathrm{mol})} \qquad (5)$$

where k is a summatory index.



(a) EA-Cy101 systems



(b) EA systems

Fig. 7 Effects of reducing initial catalyst loading on process yield, analysed using GC of the permeate (a) EA–Cy101 systems (b) EA systems.

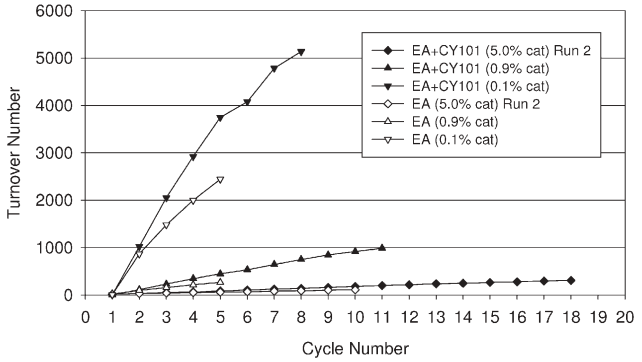


Fig. 8 Cumulative turnover numbers for each system showing the effect of reducing catalyst loading for different solvent systems.

The TON is significantly improved by using low catalyst loading in the same solvent system. For example, Fig. 8 shows the TON increases from 310 (5.0 mol% catalyst loading) up to 5100 (0.1 mol% experiment), taking all the cycles in the ethyl acetate–CyPhos®101 solvent system into account.

The benefits of the presence of CyPhos®101 are clearly shown in Fig. 7a, where over 70% yield is achieved in 4 cycles at 0.1 mol% catalyst loading. This result contrasts well with the ethyl acetate system where over 70% yield is achieved only in the initial two cycles even at 5.0 mol% catalyst loading (see Fig. 7b).

It is also interesting to note that negligible yields and conversions were observed in the first cycle for all low catalyst loadings (*i.e.* 0.9 mol% and 0.1 mol%) in both solvent systems. Subsequently, process yields increase to values over 60% in the second cycle. This may be due to lack of activation of the palladium catalyst in the initial cycle. This effect, observed by other research groups,[10,12] seems to become more significant at low catalyst loading.

In order to further investigate this observation, four reaction cycles were performed after an initial catalyst pre-activation step, in which the catalyst (0.9 mol%) was activated in the presence of BrAP, triphenylphosphine, CyPhos®101 and ethyl acetate, under the reaction conditions, but without phenylboronic acid, water and base. Pre-activation provided a process yield of 66% for the first cycle. As alluded to above, this is consistent with a reaction yield of 80% because part of the ABP remains in the retentate. For the subsequent

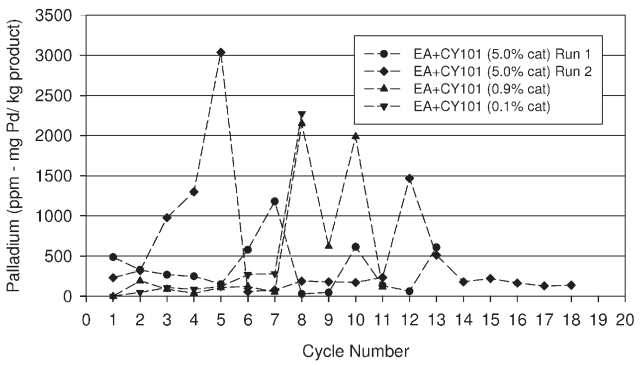


Fig. 9 Palladium loading in the nanofiltration permeate stream.

cycles, the values of the process yield increase and then decrease in a pattern similar to that obtained without catalyst pre-activation.

At low catalyst loading, the pattern of palladium levels (see Fig. 9) is similar to that observed previously (see Fig. 6), where the first five cycles were generally at consistent levels (100 ppm–1000 ppm), but spikes to higher values were seen towards the final cycles. Overall, only slight decreases in palladium content were observed with the resulting palladium level too high to be acceptable for pharmaceutical applications.

Conclusion

This study demonstrates that ionic liquids, particularly CyPhos®101, can stabilise palladium catalysts against deactivation. As a result, it enables the recycling and re-use of the catalyst with the assistance of OSN technology. Using low catalyst loading in the system enjoys the advantage of higher catalyst turnover numbers, but this is also accompanied by a more rapid rate of decline for the product yield.

OSN technology was successfully applied to the purification of the reaction products from a homogeneous post-reaction solution, initially containing ionic liquid and catalyst. The failure of two filtration stages to further reduce palladium levels suggests part of the catalyst degrades into small molecules, which the nanofiltration membrane is not able to retain. In terms of product purity, the palladium per unit mass of product in the permeate stream remains unacceptable for pharmaceutical applications without further treatment to reduce Pd levels.

Experimental

Suzuki reaction procedure

A typical procedure for Suzuki coupling using CyPhos®101 is as follows. Ethyl acetate was degassed in a 250 ml volume double necked round bottom flask using the Schlenk technique (15 min under argon). CyPhos®101 (1 ml), 4-bromoacetophenone (1 mmol, 1.0 equiv.) and phenylboronic acid (1.1 mmol, 1.1 equiv.) were added to a carousel tube. An atmosbag was inflated and evacuated three times using argon. Inside, the triphenylphosphine (0.5 mmol, 0.5 equiv.) was dissolved in degassed ethyl acetate (1 ml), tris(dibenzylidenacetone)dipalladium (0) (0.05 mmol, 0.05 equiv.) was weighed into the tube. Degassed ethyl acetate (1 ml) and 0.2 ml of the ligand solution was added along with the potassium phosphate (previously dried in an oven for an hour at 100 °C, 3.3 mmol 3.3 equiv.) and 0.4 ml of degassed, purified water. The tube was then connected to the carousel, stirring started, and left for 1 hour once the reaction mixture reached 70 °C. All reactants were purchased from Sigma Aldrich, UK apart from CyPhos®101, which was donated from Cytec Canada Inc., Canada.

OSN

All filtrations were carried out in a dead-end Sepa ST pressure cell (Osmonics, USA) at 30 bar pressure and 30 °C. The cell was immersed in a temperature controlled water bath and temperature was allowed to stabilise before any filtrations were started. The solution was agitated using a magnetic plate and a Teflon stirrer bar. STARMEM™ 122 membranes (polyimide, asymmetric type membrane, MWCO 220 g mol^{-1}), supplied by Membrane Extraction Technology Ltd, UK, were used throughout all experimental work. The membrane was preconditioned using the following process: 220 ml ethyl acetate was fed into the cell, the first 50 ml of permeate were discarded, then after collecting 100 ml more, the pressure was slowly released. The cell was then charged with the collected permeate and filtration was run again, collecting 150 ml permeate, which was returned to the cell for a third filtration. The same membrane was used throughout all the cycles and contamination between IL and purely organic systems was minimised by using two cells, one for each solvent strategy. 20–30 ml fresh ethyl acetate was permeated through the membrane in order to wash the cell and the membrane to reduce contamination.

Recycling process

After the reaction stage (see 2, Fig. 3) the recycling process began with the dilution of the post reaction mixture with 20 ml ethyl acetate. This was agitated for one hour with 20 ml of purified water (see 2, Fig. 3). After allowing phase separation, the lower aqueous phase was removed, and an aqueous sample was taken for metal analysis. The organic phase was made up to 40 ml with ethyl acetate and placed in a dead end SEPA ST pressure cell fitted with a preconditioned membrane. A 1 ml sample was taken from the nanofiltration feed for determination of feed Pd levels *via* ICP-OES. The filtration was terminated (stage 5) when 33 ml of permeate was collected. Analytical samples of the permeate were taken. The remaining retentate was then poured into a new reaction tube containing fresh base, bromoacetophenone and phenylboronic acid, but no additional IL, catalyst or ligand. Finally the reaction was restarted.

Analytical techniques

Gas chromatography was used to determine the concentration of 4-acetyl-biphenyl and bromoacetophenone using the 6850 Series II from Agilent Technologies, fitted with a flame ionisation detector and a HP-1 capillary column 30 m × 0.32 mm nominal diameter, 0.25 mm film thickness 100% dimethylpolysiloxane phase. A coefficient of variation for this assay was estimated to be below 2.5%, based on 44 measurements of a standard solution of ABP and BrAP at concentrations of 26 mM.

Inductively coupled plasma optical emission spectrometry (ICP-OES) was used to determine metal concentrations (Pd, K, B) in the nanofiltration feed, permeate and water wash. ICP analysis was carried out using a Perkin Elmer 2000DV ICP-OES. After initial sampling of the water washes the remaining water was evaporated, then digested with aqua regia to dissolve all the palladium black, to obtain data about levels of precipitation *via* ICP-OES. Each sample was analysed three times and the coefficient of variation for the values obtained was estimated to be lower than 4%.

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