

Review

Toward green catalytic synthesis—Transition metal-catalyzed reactions in non-conventional media

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Abstract

Solvents play a critical role in “greening” synthetic chemistry, and this is also true in catalytic organic synthesis. This review attempts to summarize the progress made in the past a few years on homogeneous and heterogeneous catalytic reactions in the non-conventional solvents, water, ionic liquids, supercritical carbon dioxide and fluorous carbons, with the focus on those catalyzed by transition metal complexes. The reactions covered include hydrogenation, hydroformylation, carbonylation, Heck reactions, Suzuki and Stille couplings, Sonogashira reactions, allylic substitution, olefin metathesis, olefin epoxidation and alcohol oxidation.

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Keywords: Catalysis; Transition metal complexes; Solvent effects; Water; Ionic liquids; Supercritical carbon dioxide; Fluorous solvents

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1. Introduction

Organic synthesis is a central theme in many disciplines of science ranging from chemistry through biology to materials. Over the last one and a half centuries, organic synthesis has evolved to such a degree of sophistication that it allows molecules of almost any complexity to be constructed. In the way of arriving at this spectacular achievement, catalysis, as the foundational pillar to green chemistry, has played a vital role. However, in traditional catalytic processes, organic solvents are usually employed as the reaction media, often creating a great deal of safety, health and environmental issues due to their flammability, toxicity and volatility. In recent years, the importance of environmentally benign synthesis has been increasingly recognized and parameters, such as *E*-factor [1], atom efficiency [2] and the “12 Principles of Green Chemistry” [3] are often considered as essential driving force in the quest for sustainable chemical processes. Solvents are a key component in making a process green. A recent study suggests that rigorous management of solvent use could make the greatest improvement in greener organic synthesis [4]. The best solvent is no solvent and if a solvent is needed, green or potentially green alternatives should be considered. Preferentially, such alternative solvents should also enable easy catalyst separation and recycle. While a number of reactions have been shown to proceed under solvent-free conditions, most synthetic reactions still call for the use of solvents at the present; hence alternatives to common organic solvents have been actively sought [5]. In this context, water, supercritical CO₂ (scCO₂), ionic liquid (ILs) and fluorinated solvents have received the most significant attention in the last decade or so.

Generally speaking if a solvent has to be used, water would represent a best choice. It is cheap, readily available, non-toxic, non-flammable and safe to environment. Of additional importance to catalysis is that water allows for facile catalyst separation and recycles through a biphasic catalysis mode due to its low miscibility with most organic compounds [6,7]. ILs, composed entirely of organic cations and organic or inorganic anions, display physicochemical properties, *e.g.* low melting point, negligible vapour pressure, low flammability, tunable polarity and miscibility with other organic or inorganic compounds, that are appealing to catalysis and separation processes [8]. ILs have low solubility towards low-polarity compounds, such as ethers or alkanes, and they are also insoluble in scCO₂ while the latter can be highly soluble in ILs [9]. Hence, the application of biphasic catalysis with ILs is possible, and even for monophasic catalysis, catalyst/product separation can be readily practiced by extraction of the product, leaving the catalyst in ILs for reuse. Interestingly, in most cases transition metal catalysts can dissolve or be “immobilized” in ILs and appear to be stable without the use of specially designed ligands, a great advantage over aqueous-phase catalysis where water-soluble ligands are generally called for.

In addition to water and ILs, scCO₂ and fluorinated solvents have also been extensively investigated as alternatives to common organic solvents. ScCO₂ is non-toxic, non-flammable, inexpensive, relatively inert towards reactive compounds and

readily separable from products upon depressurization. Furthermore, its low viscosity and high diffusivity properties confer advantages on reactions with mass transfer problems. In contrast to water and ILs, however, scCO₂ is apolar (CO₂ has no dipole moment but has a quadrupole) and generally only suitable for compounds of low polarity in catalytic processes [10]. Fluorinated solvents, with perfluorinated alkanes being most representative, possess unusual physicochemical properties, such as low dielectric constants, high chemical and thermal stability, and low toxicity. They commonly exhibit temperature-dependent miscibility with organic solvents, *e.g.* immiscible at low temperature but miscible at elevated temperature, thus allowing for homogeneous catalysis at high temperature and easy catalyst/product separation at ambient conditions. This property is of particular importance to biphasic catalysis [11].

This review is a follow-up of a paper we published in 2004, which summarized the major progress made in transition metal catalysis in the non-conventional media aforementioned up to 2003 [12]. In this review, we have attempted to provide an update on the progress made since then. Given the sheer number and diversity of publications that have appeared in the area in the past 3 years, it becomes almost impossible to present a comprehensive story in a limited space. Therefore, we have restricted ourselves to, as far as we are aware, the most representative examples that have appeared since 2003 and up to mid 2006. However, earlier references are brought up whenever necessary. Quite likely, some important contributions have escaped our attention, and we apologise for our negligence. Gratifyingly, excellent reviews on each specific solvent in catalysis have been published, where more details can be accessed [13–17], and on the completion of this paper, *Adv. Synth. Catal.* dedicated an entire issue to multiphase catalysis, green solvents and immobilization [18].

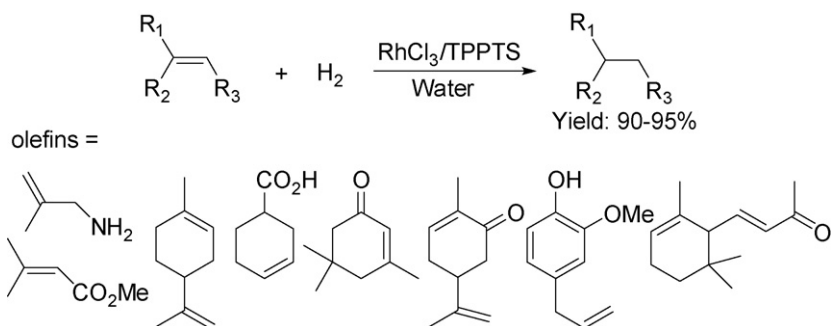
2. Catalytic reactions in non-conventional media

2.1. Hydrogenation

Hydrogenation is a totally atom-economic reaction and belongs to the most important transformations in chemical industry. Hydrogenation is also one of the most studied reactions in the alternative solvents, with most examples documented in water.

2.1.1. Achiral hydrogenation

Water has been shown to be a suitable solvent for hydrogenation [19]. Water-soluble catalysts play an important role in the process, and achiral and chiral water-soluble ligands have been well documented in the literature [6]. For example, Larpent et al. reported that the hydrogenation of various olefins proceeded smoothly at room temperature and an atmosphere of H₂, with a yield of 90–95% and complete chemoselectivity towards C=C bonds, by using RhCl₃ in the presence of the exceedingly water-soluble phosphine, TPPTS [TPPTS = P(*m*-C₆H₄SO₃Na)₃] (Scheme 1) [20]. In the case of dienes, the less hindered C=C bond was first hydrogenated and the reaction could be terminated at the monoene stage.



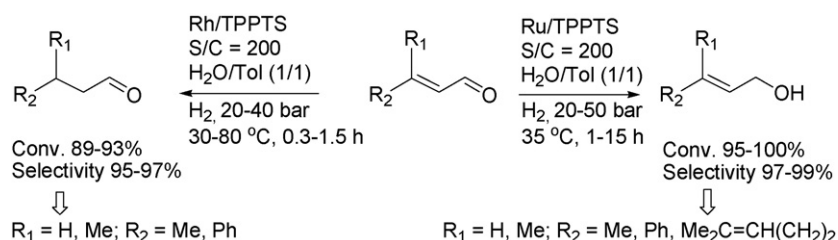
Scheme 1.

Recently, Bajaj and co-workers reported that the water-soluble catalyst, $\text{RuCl}_2(\text{TPPTS})_3$, catalyzed hydrogenation of unsaturated hydrocarbons, such as 1-alkenes, styrene, cyclooctene, cyclooctadidene and benzene, in water under mild reaction conditions (H_2 , 10 bar, 150°C , 7 h), affording moderate to high conversions [21]. Among the olefins, aliphatic unsaturated hydrocarbons can be hydrogenated more efficiently than aromatic ones. The authors also described that the selectivity of hydrogenation of benzene was partially shifted to favour cyclohexene by the addition of a specific amount of ZnCl_2 . The ruthenium complexes, $\text{Ru}(\text{CO})_3(\text{TPPMS})_2$ ($\text{TPPMS} = (\text{C}_6\text{H}_5)_2\text{P}(m\text{-C}_6\text{H}_4\text{SO}_3\text{Na})$) [22], $\text{RuH}_2(\text{CO})(\text{TPPMS})_3$ [22] and $[\text{RuH}(\text{CO})(\text{NCMe})(\text{TPPMS})_3][\text{BF}_4]$ [23], were also shown to be efficient catalyst precursors for the hydrogenation of such olefins as 1-hexene, styrene and allylbenzene in a water/*n*-heptane (1:1) mixture under moderate conditions (28 bar H_2 , $S/C = 100/1$, $80\text{--}100^\circ\text{C}$, 6–8 h), to give high selectivities with feasible catalyst recycle. For example, the monohydride complex could be recycled several times, maintaining the same activity without leaching of ruthenium.

Regioselective hydrogenation of α,β -unsaturated substrates is also possible in an aqueous phase, in particular under aqueous–organic biphasic conditions. Rh or Ru complexes are often the catalyst of choice in this respect. In general, hydrogenation at $\text{C}=\text{C}$ double bonds is accomplished by Rh-complex while the reduction of $\text{C}=\text{O}$ bonds is achieved by Ru-complex. For example, as shown in Scheme 2, in a water–toluene (1:1) mixture α,β -unsaturated aldehydes were hydrogenated at the $\text{C}=\text{C}$ bond by Rh/TPPTS with up to 93% conversions and 97% selectivities, and at the $\text{C}=\text{O}$ group by Ru/TPPTS with up to 100% conversions and 99% selectivities. The catalyst could be recycled to yield even a slightly higher activity and selectivity [24].

The water-soluble tetranuclear complex $\text{Rh}_4(\text{O}_2\text{CPr})_4\text{Cl}_4(\text{MeCN})_4$ ($\text{Pr} = n\text{-propyl}$) was reported to selectively catalyze the hydrogenation α,β -unsaturated alcohol, ketone, nitrile, carboxylic acid and amide substrates at the $\text{C}=\text{C}$ bond under 1 atm of H_2 at room temperature [25]. Ru(II), Rh(I) and Rh(III) complexes of *N*-methyl-PTA (PTA-Me, PTA = 1,3,5-triaza-7-phosphaadamantane) such as $[\text{RuI}_4(\text{PTA-Me})_2]$, $[\text{RuI}_2(\text{PTA-Me})_3(\text{H}_2\text{O})]\text{I}_3$ and $[\text{Rh}_4(\text{PTA-Me})_2]\text{I}$ were shown to be active catalysts for the hydrogenation of cinnamaldehyde (CNA) at $\text{C}=\text{C}$ bond with Rh and at $\text{C}=\text{O}$ group with Ru in a biphasic mixture, $\text{H}_2\text{O}/\text{toluene}$ or $\text{H}_2\text{O}/\text{chlorobenzene}$ [26]. For instance, CNA was converted to $\text{PhCH}_2\text{CH}_2\text{CHO}$ in 95% conversion with 84% selectivity and a TOF of 190 h^{-1} by using $\text{RhI}_4(\text{PTA-Me})_2$ in $\text{H}_2\text{O}/\text{toluene}$. To some extent, however, the selectivity at $\text{C}=\text{C}$ bond or $\text{C}=\text{O}$ group is dependent on other reaction conditions. Examples were recently reported by Peruzzini and co-workers, who showed that the selectivity of $\text{CpRuCl}(\text{PTA})_2$ ($\text{Cp} = \eta^5\text{-C}_5\text{H}_5$), in the hydrogenation of benzylidene acetone (BZA) ($S/C = 200$) at the $\text{C}=\text{C}$ bond to give 4-phenyl-butan-2-one in $\text{H}_2\text{O}/n\text{-octane}$ (1/2, v/v), varied with the reaction temperature [27]. At 80°C and 450 psi of H_2 after 13 h, the selectivity could reach 90% albeit with a low conversion of 26%, but when the temperature was increased to 130°C , the selectivity dropped to 76%, though with a higher activity. The same trend was observed by using the catalyst $\text{Cp}^*\text{RuCl}(\text{PTA})_2$ ($\text{Cp}^* = \eta^5\text{-C}_5\text{Me}_5$). Interestingly, more recent studies by the same group show that by increasing the ratio of $\text{H}_2\text{O}/n\text{-octane}$ from 1:2 to 3.5:1, the same reaction provides a >99% selectivity with good conversion (76% with both $\text{CpRuCl}(\text{PTA})_2$ and $[\text{CpRu}(\text{MeCN})(\text{PTA})_2][\text{PF}_6]$) under similar conditions ($S/C = 200$, 450 psi of H_2 , 80°C , 16 h) [28].

Recent studies have revealed the effect of a variety of other parameters on hydrogenation, *e.g.* the pressure of H_2 , temperature, catalyst concentration, ratio of catalyst to ligand, initial



Scheme 2.

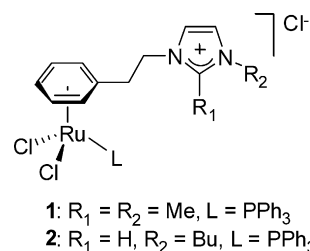
concentration of substrate and solution pH, and their effects on the chemoselectivity in the hydrogenation of α,β -unsaturated aldehydes [29–31]. For instance, in the case of the Rh-TPPTS catalyzed process, higher H_2 pressure shifted the hydrogenation towards the C=O bond, while a large excess of TPPTS ligand favoured the saturation of C=C bond [30]. The selectivity was independent of the amount of catalyst, however. Solution pH has been found to be important as well. Joó and co-workers reported that the selective hydrogenation of *trans*-CAN at the C=C bond was achievable at a low pH (<5) with 1 bar of H_2 ; but the selectivity favoured the C=O bond when the pH was increased to >7 [31]. On the other hand, selective saturation of the C=O bond could also be achieved at a low pH, but at a higher H_2 pressure of 8 bar. The observation was explained as a result of the concentration of the active catalyst species involved in the reaction, $RuClH(TPPMS)_3$ and $RuH_2(TPPMS)_4$, which vary with the solution pH and H_2 pressure. The former was selective toward the C=C bond while the latter to the carbonyl.

More recently, a DFT investigation of the Ru-catalyzed selective hydrogenation of α,β -unsaturated aldehydes in aqueous/organic biphasic media showed that the favoured C=O hydrogenation under basic conditions, which favour the formation of $RuH_2(PR_3)_4$, is due to the presence of water, which forms hydrogen bonding with the aldehyde [32]. At the same time, a similar mechanistic study by Joó and co-workers [33] revealed that the selective reduction of C=C over C=O by $RuClH(PR_3)_3$ under acidic conditions is due to a lower barrier of C=C versus C=O insertion into the Ru–H bond [34]. It is worth noting that both studies show that, being involved in various steps of the catalytic cycle, water as solvent is not an innocent spectator. Regioselective hydrogenation of α,β -unsaturated aldehydes has a wide practical application, for example, in the production of allylic alcohols and cinnamyl alcohols [29,30,35].

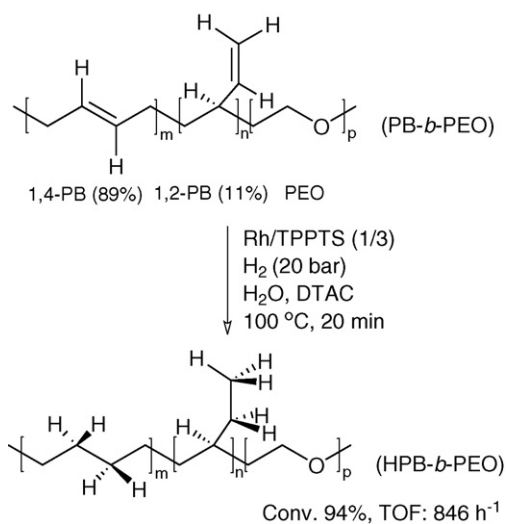
Hydrogenation of simple ketones and aldehydes can also be carried out in water or water/organic biphasic solvents. The water-soluble iridium complex $[Cp^*Ir^{III}(H_2O)_3]^{2+}$ was shown

to be active for the hydrogenation of carbonyl compounds and alkenes in a pH range of –1 to 4 in water under mild reaction conditions (1–7 bar H_2 , 25 °C) [36]. The formation of pH-dependent catalytic species was key in the reaction. Similar reports were presented recently, suggesting that the active catalyst species [37] or the stereoselectivity of the catalyst [38] could be controlled by the pH of the aqueous phase.

Dyson and co-workers recently reported the use of imidazolium-tagged Ru-arene complexes **1** and **2** in hydrogenation of styrene in water/cyclohexane (1:2) [39]. The reaction proceeded readily under mild conditions (0.1 mol% catalyst, $S/C = 1000$, 40 bar H_2 , 80 °C, 120 min) with the catalyst being reusable, albeit with slightly decreased activity in recycle runs. Catalysts of this type have also found use in catalysis in imidazolium ILs (*vide infra*).



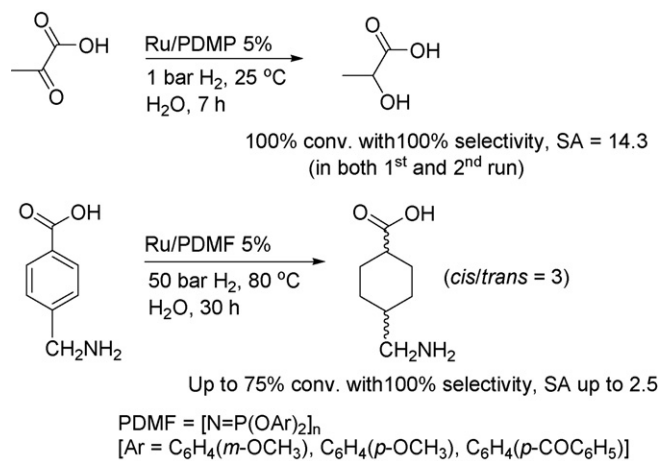
Hydrogenation of unsaturated polymers in water is also possible. Such reactions have been successfully carried out in either conventional organic solvents [40] or other media, such as ILs [41,42], and very recently Papadogianakis and co-workers reported an efficient hydrogenation of polybutadiene-1,4-*block*-poly(ethylene oxide) catalyzed by Rh/TPPTS complexes in water, as shown in Scheme 3 [43]. The reaction was shown to be homogeneous and proceeded in PB-*b*-PEO/DTAC nanomicelles (DTAC = dodecyltrimethylammonium chloride, a cationic surfactant), to give a high conversion with exceptionally high catalytic activities ($TOF > 840 h^{-1}$). The catalyst could be recycled and reused, maintaining high catalytic activity in a consecutive run even at a rhodium concentration of only 1 ppm in water.



Scheme 3.

Supported nanoparticles have been used to catalyze hydrogenation in the aqueous phase. Ru nanoparticles immobilized on the water-soluble polymer polyorganophosphazenes ($-[N=PR_2]_n-$) was found to be an active catalyst for the hydrogenation of unsaturated ketones or aromatic compounds such as pyruvic acid and *p*-aminomethylbenzoic acid in water [44]. For example, as shown in Scheme 4, pyruvic acid was completely reduced to lactic acid by Ru on PDMP (PDMP = polydimethylphosphazene) in 100% selectivity and SA of 14.3 (SA, specific activity; moles of converted substrate per gram atom ruthenium per hour) under mild conditions; no catalyst deactivation was observed in the recycle runs.

Heterogeneous nanocatalytic hydrogenation in aqueous phase has been reported as well. Mévellec and Roucoux reported that *N*-, or *O*-heteroaromatic compounds can be hydrogenated in water under mild conditions, catalyzed by Rh(0) colloidal suspension stabilized by highly water-soluble *N,N'*-dimethyl-*N*-cetyl-*N*-(2-hydroxyethyl)ammonium bromide or chloride (HEA 16X, X = Br or Cl) (Scheme 5) [45]. The cat-

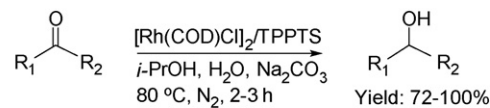


Scheme 4.

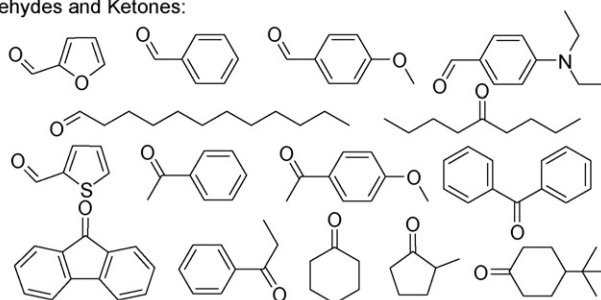
alyst could be reused without losing its activity. However, no catalytic activities were detected with sulfur compounds, such as thiophene.

The pH value of reaction solution has a significant influence on catalytic performance. For example, by studying a Ru-catalyzed hydrogenation of benzene in an aqueous biphasic system in pH 1.5–12.4, Dagueuet and Dyson showed that at pH < 6.7 the catalysis was homogenous, giving a slow reaction (TOF < 9 h⁻¹), whereas at pH > 8.5 the catalysis shifted to a heterogeneous regime with increased nanoparticle formation, leading to dramatically enhanced activity (TOF up to 100 h⁻¹) [46].

In addition to Rh(0) and Ru(0), Pd-nanoparticles were also shown to be active catalyst precursors for heterogeneous hydrogenations in aqueous phase [47–52]. For instance, selective hydrogenation of dehydrolinalool (3,7-dimethyloct-6-ene-1-yne-3-ol) to linalool (3,7-dimethyloct-1,6-diene-3-ol) catalyzed by Pd nanoparticles, formed in poly(ethylene oxide)-*block*-2-vinylpyridine (PEO-*b*-P2VP) micelles, was studied by varying the ratio of *i*-PrOH/H₂O and the pH of the reaction medium [48]. The highest selectivity (99.4%) was obtained at pH 9.4 and 95 vol% of *i*-PrOH and the highest TOF was found to be 24.4 h⁻¹ at pH 13.0. Another example is that benzonitrile was cleanly hydrogenated to benzylamine by Pd/C in the presence of NaH₂PO₄ in a mixture of H₂O/CH₂Cl₂ under mild reaction



Aldehydes and Ketones:



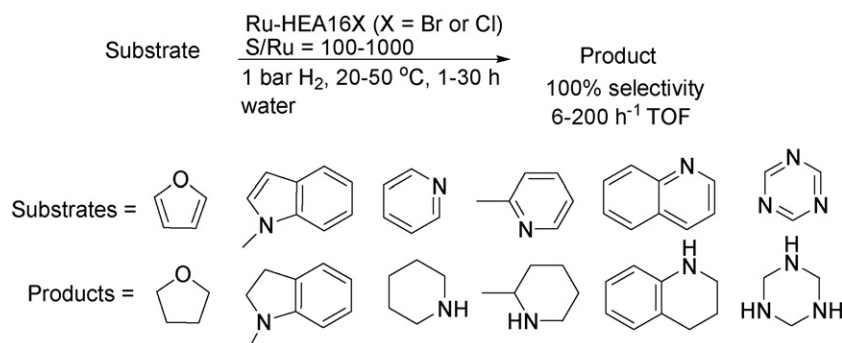
Scheme 6.

conditions (30 °C, 6 bar H₂) to give complete conversion with 95% selectivity and 90% isolated yield [52].

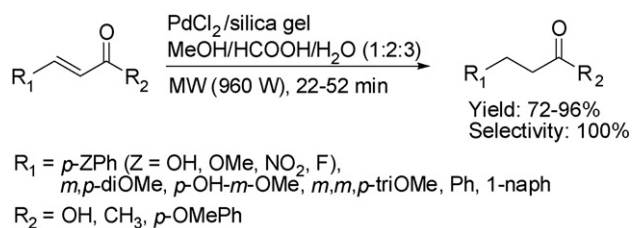
Catalytic reductions of nitrate and nitrite in water were also feasible [53–57]. Since the subject falls out of the focus of this review, it will not be discussed here.

Transfer hydrogenation in water has attracted a lot of recent attention. An early example reported by Joó and co-workers shows that benzaldehydes, CNA, crotoaldehyde, 1-citronellal and citral could be reduced at the C=O bond by HCOONa in the presence of RuCl₂(TPPMS)₂ to give high conversion, typically over 98% [58]. Recently, Ogo and co-workers reported that both water-soluble and water-insoluble ketones could be reduced by HCOONa at 70 °C, catalyzed by the water-soluble complex [(η⁶-C₆Me₆)Ru(bpy)(H₂O)]SO₄ (bpy = 2,2'-bipyridine), giving rise to yields over 97% and TOF up to 153 h⁻¹ [59]. The solution pH was also reported to be important for transfer hydrogenation [59,60]. More recently, Ajiou and Pinet reported that various aliphatic/aromatic aldehydes and ketones were quantitatively hydrogenated by *i*-PrOH to the corresponding alcohols in water under mild conditions (Scheme 6) [61]. Water-soluble [Rh(COD)Cl]₂/TPPTS complex (COD = 1,5-cyclooctadiene) was employed as catalyst. The catalyst could be successfully recovered by simple decantation and reused with only negligible loss of activity.

In addition, the complex Cp^{*}RuCl(PTA)₂ was reported to be a highly active catalyst for the reduction of BZA to the saturated



Scheme 5.



Scheme 7.

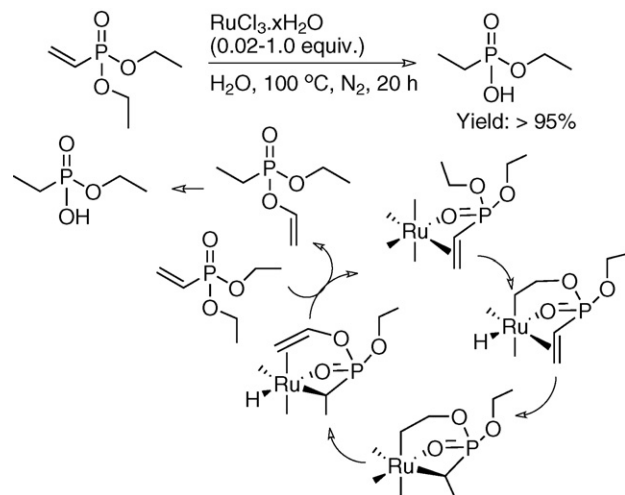
ketone 4-phenyl-butan-2-one by HCOONa/H₂O/MeOH (97.4% conversion with 99.5% selectivity at 90 °C after 6 h), and for the reduction of CNA to saturated alcohol 3-phenyl-1-propanol by HCOONa/H₂O (99.4% conversion with 87% selectivity at 90 °C after 5 h) [28].

A chemoselective transfer hydrogenation of α,β -unsaturated carbonyl compounds at the C=C bond was achieved by silica-supported PdCl₂ with a combination of MeOH/HCOOH/H₂O (1:2:3) as hydrogen source and solvent under microwave (MW) heating [62]. As shown in Scheme 7, a series of carbonyl compounds were readily reduced to the corresponding saturated ketones in 72–96% isolated yields with 100% selectivities.

A new class of neutral and cationic Rh(I) complexes bearing the water-soluble aminophosphine cage ligand PNT (PNT = 7-phospha-3-methyl-1,3,5-triazabicyclo[3.3.1] nonane) was reported to be an effective catalyst for selective transfer hydrogenation of BZA (C=C was saturated) and acetophenone using HCOONa as hydrogen source in water at a 1% catalyst loading [63].

As depicted in Scheme 8, vinyl phosphonic diethyl ester can be hydrogenated in water to yield ethyl-phosphonic monoethyl ester in quantitative yield by using 2% of RuCl₃·3H₂O [64]. It is worth pointing that there was no ancillary ligand, nor was there an external hydrogen source. As outlined in the catalytic cycle, it was believed that an intermolecular hydrogen transfer from P–OEt to the olefin via C–H activation was involved in the catalytic process.

Turning attention to ILs, it is interesting to note that hydrogenation was one of the first catalytic reactions to be



Scheme 8.

attempted in the now most-widely-used imidazolium ILs. As early as 1995, Chauvin and co-workers [65] and, at about the same time Dupont and co-workers [66], reported Rh-catalyzed hydrogenation in ILs, with the catalyst and solvent both being recoverable. Recent examples from the Dupont group show that olefins, such as styrene, methyl methacrylate and 4-vinylcyclohexene, could be readily hydrogenated in the IL [bmim]PF₆ (bmim = 1-butyl-3-methylimidazolium) at 75 °C and 4 bar of H₂ by iridium nanoparticles generated from [IrCl(COD)]₂, furnishing up to 91% conversion together with 91% selectivity and 6000 h⁻¹ TOF. Moreover, the catalyst could be separated by simple decantation and recycled seven times [67]. Following this success, the same research group has widened the investigation on metal-mediated hydrogenation of olefins in ILs [68–73]. For instance, simple olefins such as 1-hexene and cyclohexene could be readily hydrogenated by Ru⁰ nanoparticles, generated from the reduction of [Ru(COD)(COT)] (COT = 1,3,5-cyclooctatriene) by H₂ in IL, to afford 500 TON and up to 1000 h⁻¹ TOF under 4 atm of H₂ at 75 °C in [bmim]BF₄/PF₆. For benzene only partial hydrogenation was observed, however [71]. 1-Hexene could be completely converted to hexane by Ru⁰ nanoparticles, *in situ* formed from the reduction of RuO₂, in the IL [bmim]BF₄/PF₆/CF₃SO₃ over 0.7–4.5 h under mild conditions, and the catalyst could be recycled 17 times with a total TON greater than 110,000 without any loss of activity [72]. A further example is 1,3-butadiene, which could be selectively reduced to 1-butene with up to 97% selectivity by Pd⁰ nanoparticles in [bmim]BF₄ under similar conditions [73].

The cluster [Ru₆C(CO)₁₆]²⁻, among others, *e.g.* [Hf(CO)₁₁]⁻, [HWOs₃(CO)₁₄]⁻ and [HOS₄(CO)₁₂]⁻, was shown to be an active catalyst for the hydrogenation of simple olefins and cyclic dienes in a variety of ILs [74]. At 100 °C and 50.7 bar of H₂, styrene could be converted to ethylbenzene in [bmim]BF₄ in a 93% yield with TOF of 587 h⁻¹, and cyclic dienes could be selectively hydrogenated to cyclic monoenes with over 91% selectivity. The imidazolium-tagged Ru-arene complex **2** was also tested as catalyst for hydrogenation of styrene to give ethylbenzene in [C₂pic]NTf₂/cyclohexane (1:2) (C₂pic = *N*-ethyl-3-methylpiccolium) under mild conditions; but the catalyst activity was low [39].

The complex RuCl₂(TPPMS)₃(DMSO) was reported to be active for the hydrogenation of benzene in [bmim]PF₆ and stable enough to be recycled several times with little loss of catalytic activity [75]. A report by Jiang and co-workers described that polystyrene-*b*-polybutadiene-*b*-polystyrene (SBS) was selectively hydrogenated at the butadiene segment by Ru/TPPTS in the presence of PPh₃ (Ru/TPPTS/PPh₃ = 1:5:2) in a polyether-modified, ammonium-based IL at 100 °C, 50 bar of H₂ for 12 h, to give a total hydrogenation degree of 85%; the catalyst was recycled three times without any loss in catalytic activity [41].

Hydrogenation in IL with more traditional heterogeneous catalysts was also shown to be possible. Thus, halonitrobenzenes could be reduced to the corresponding haloanilines over Raney nickel, Pt/C and Pd/C in various ILs [Rmim]BF₄/PF₆ (R = C₂H₅, C₄H₉, C₆H₁₃, C₈H₁₇ and CH₃OC₂H₅) [76]. A series of chloro-, bromo- and dichloronitrobenzenes were readily hydrogenated at

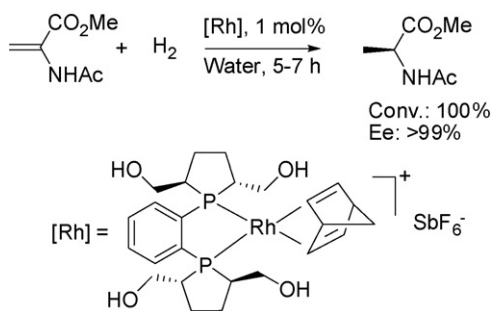
to enhanced H₂ concentration in a CO₂-expanded liquid phase [92].

Fluorous fluids have found use as solvent in catalytic hydrogenation as well, but to a lesser degree than H₂O or ILs. Similar to catalysis in scCO₂, in order to increase the catalyst solubility in a fluorous solvent, it is also necessary to modify the ligand by introducing a fluorous tail. This leads to a powerful new means in catalysis, *viz.* fluorous biphasic catalysis. The readers are referred to reference [16] for early development in the area. Recent examples include hydrogenation of the C=C bonds of various functionalized olefins such as 2-cyclohexene-1-one and cinnamic acid derivatives by rhodium in combination with fluorous-soluble phosphine, *e.g.* P(*p*-C₆H₄OCH₂CH₂C₇F₁₅)₃, in the biphasic D-100/ethanol (D-100 is mainly made of perfluorooctane) under 1 bar of H₂ at room temperature; the catalyst was recyclable [93]. The hydrogenation of allylic alcohol to *n*-propanol by a fluorous-soluble dendrimer-encapsulated Pd⁰ catalyst was accelerated by introducing CO₂ in a fluorous–organic mixture; the acceleration may result from CO₂ being soluble in both the organic solvent and fluorocarbon [94].

2.1.2. Asymmetric hydrogenation

The alternative solvents are also attractive reaction media in enantioselective hydrogenation, as they may enable clean synthesis of important fine chemicals and pharmaceutical intermediates with easy separation and recycle of expensive chiral catalysts. In many cases, however, chiral catalysts in such media led to reduced enantioselectivities and/or activities than in a homogeneous organic phase, especially in the case of water in the early days [95–97]. This is partly due to factors such as catalyst modification, altered solvation, diffusion control, and reduced substrate and catalyst solubility.

Aqueous-phase asymmetric hydrogenation generally necessitates the use of water-soluble ligands. These chiral ligands are usually prepared by the incorporation of an anionic group, such

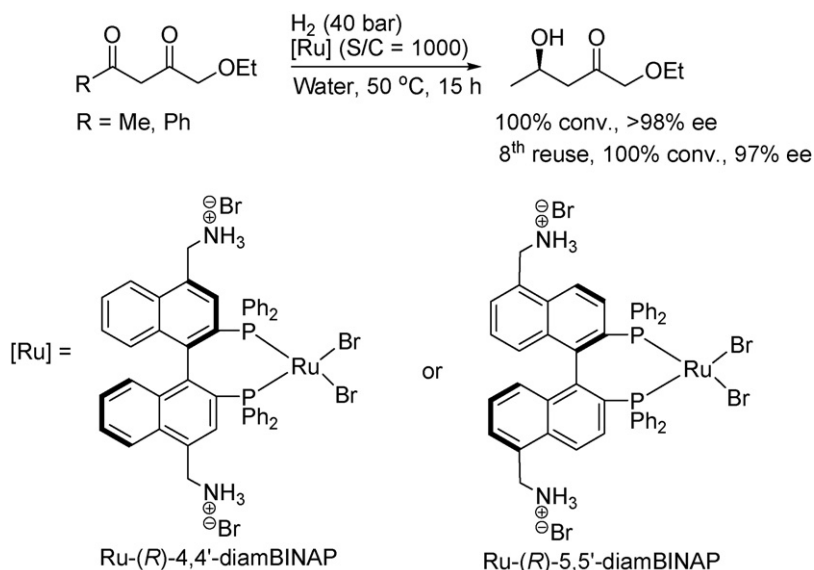


Scheme 11.

as sulfonate, or a cationic group, such as quaternary ammonium ion, or a neutral hydrophilic group, such as polyether. The water-soluble, hydroxy-functionalized complex [RhL(NBD)][SbF₆] (NBD = norbornadiene), shown in Scheme 11, has proved to be an effective catalyst for the reduction of methyl 2-acetamidoacrylate, affording 100% conversion with >99% ee in water at *ca.* 3 bar of H₂ at room temperature in 5–7 h [98]. Moreover, the catalyst was stable, being recyclable up to four times without losing any activity and enantioselectivity.

Jacobs and co-workers [99] described the Rh-EtDuPHOS catalyzed hydrogenation of methyl 2-acetamidoacrylate, which proceeded successfully in a mixture of [bmim]PF₆/H₂O (1:1, v/v) at 20 °C, 5 bar of H₂, furnishing 68% conversion with 96% ee in 20 min reaction time. On the contrary, in [bmim]PF₆ without water, there was no activity and selectivity at all. The role of water was ascribed to helping create a well-mixed “emulsion-like” system.

Hydrophilic BINAP derivatives are another versatile ligands in asymmetric hydrogenation in water. In recent examples, 4,4' and 5,5'-diaminomethyl-BINAPs were synthesized by Lemaire and co-workers and their Ru complexes were shown to give readily asymmetric reduction of β-ketoesters with excellent ee's (>97%) in water (Scheme 12) [100]. The catalyst could be recycled up to eight times without loss in reactivity and enantio-

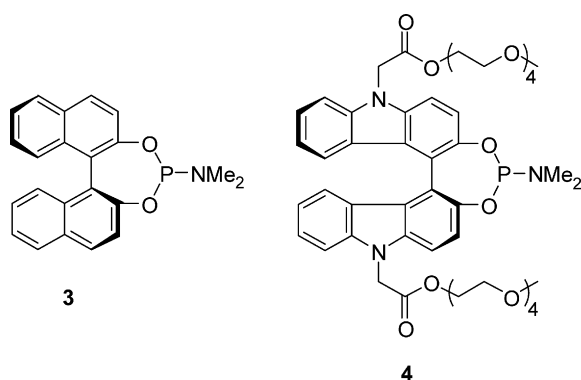


Scheme 12.

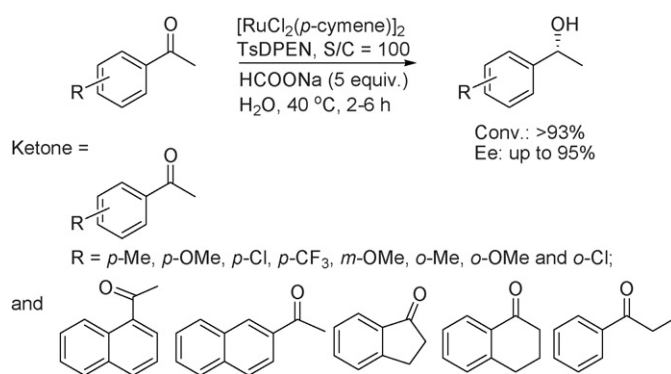
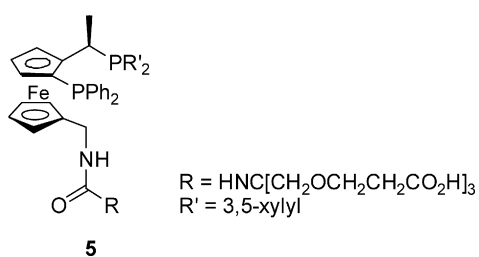
electivity. The authors have further shown that the same ligands depicted in Scheme 12 could also be used in the Ru-catalyzed hydrogenation of ethyl trifluoroacetate in an acidic aqueous medium (1.0 ml water, 0.125 ml acetic acid and 0.125 ml trifluoroacetic acid) to give *ca.* 70% ee, one of the best enantioselectivities obtained for the reduction of this substrate with Ru-BINAP or its derivatives [101]. The improved selectivity was suggested to be due to the presence of an acid-favored equilibrium between the keto-enol-hydrate or hemiketal involved in the catalytic cycle.

A report by Cervený and co-workers described Ru-(*R*)-BINAP catalyzed asymmetric hydrogenation of methyl acetoacetate in methanol, both the activity and selectivity being improved by the addition of 3 wt.% of water (TOF increased from 98 to 594 h⁻¹ and selectivity from 77 to 99.9%) [102]. Water was considered to restrict acetal formation in the initial stage of the hydrogenation. Nevertheless, addition of more than 5 wt.% of water caused a drop in both TOF and ee.

The phosphoramidites, (*S*)-MonoPhos (**3**) derived from (*S*)-BINOL and (*S*)-PegPhos (**4**) from (*S*)-BICOL, were recently reported to be viable for Rh-catalyzed enantioselective hydrogenation of *N*-acyl dehydroalanine in water [103]. Due to its better solubility in water, the PegPhos (**4**) was shown to be more effective than MonoPhos (**3**) in both activity and selectivity, providing TOF of 55 h⁻¹ and 82% ee. By addition of a co-solvent MeOH or a surfactant sodium dodecyl sulfate (SDS), the reaction rate was dramatically increased, giving up to a TOF of 1200 h⁻¹ in the MeOH–H₂O mixture, accompanied with a slightly higher enantioselectivity (89% ee).



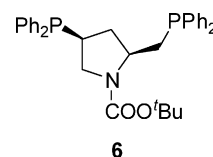
Among a series of water-soluble diphosphine ligands, the modified Josiphos **5** was reported by Blaser and co-workers to be suitable for the diastereoselective hydrogenation of folic acid disodium salt in water to give *L*-tetrahydrofolic acid, a pharmaceutically relevant intermediate, with 97% conversion and up to 49% diastereoselectivity at 30 °C after 12 h [104].



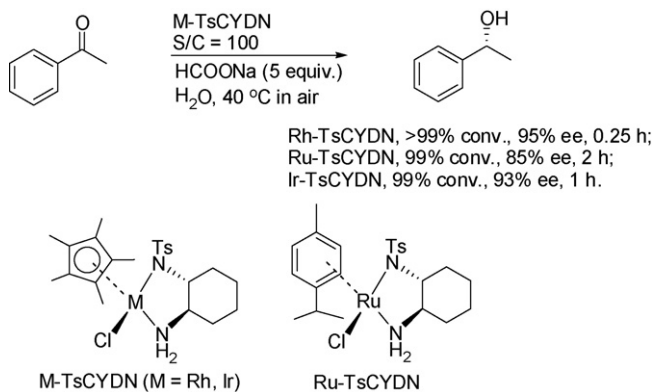
Scheme 13.

Miller and co-workers reported that the heterogeneous Ru/C could be used to reduce the amino acid *L*-alanine to *L*-alaninol in >90% yield with >97% selectivity and 99% ee under 69 bar H₂ at 100 °C in an acidic aqueous phase [105]. A kinetic study predicted that the acidified solution was necessary to give high conversions. Under such conditions, the amino acid would be protonated and so readily hydrogenated [106].

Amphiphiles or surfactants are known to promote hydrogenation in water in both rate and ee [107,108]. An example is seen in the asymmetric reduction of (*Z*)- α -acetamidocinnamate by a Ru-BPPM (**6**) catalyst, which was speeded up to 15-fold with ee's being improved from 78 to 94%, in the presence of SDS under aqueous micellar conditions [107]. The use of polymerized or immobilized amphiphiles could avoid potential phase separation, albeit at the expense of the reaction rate. The surfactant HEA16Cl-stabilized Pt(0) nanoparticles, modified with (–)-cinchonidine, have been shown to efficiently catalyze the asymmetric hydrogenation of ethyl pyruvate in a biphasic system of water/substrate at 25 °C under 40 bar of H₂, giving rise to a complete reaction with ee up to 55% at 1 h reaction time [108]. Both the conversion and ee were higher than those without using any surfactant.



Asymmetric transfer hydrogenation in water has been successfully demonstrated recently. Among the effective ligands discovered to date, perhaps the most notable one is the diamine-based TsDPEN (*N*-(*p*-toluenesulfonyl)-1,2-diphenylethylenediamine) originally developed by Hashiguchi, Ikariya and Noyori et al. [109]. TsDPEN and its derivatives have been shown to be particularly viable ligands for aqueous-phase asymmetric transfer hydrogenation of ketones, with or without any modifications and under both homogeneous and heterogeneous conditions. Thus, as shown in Scheme 13, Xiao's group demonstrated that the Ru-(*R,R*)-TsDPEN catalyst generated *in situ* from [RuCl₂(*p*-cymene)]₂ and (*R,R*)-TsDPEN was very efficient for asymmetric transfer hydrogenation of various ketones in HCOONa–H₂O, affording ee's up to 95% and significantly faster rates than in HCOOH–NEt₃ azeotrope [110]. With no



Scheme 14.

modification to the water-insoluble ligand, the catalysis was biphasic. This did not lead to slower rates than the homogeneous reaction in HCOOH–NEt₃, however.

More recently, the same group showed that M-(*R,R*)-TsCYDN (M = Rh, Ir, or Ru, TsCYDN = (1*R*,2*R*)-*N*-(*p*-toluenesulfonyl)-1,2-cyclohexanediamine), derived *in situ* from (*R,R*)-TsCYDN in combination with [Cp**RhCl*]₂, or [Cp**IrCl*]₂ or [RuCl₂(*p*-cymene)]₂, were robust catalysts for the reduction of aromatic ketones by HCOONa in water and in air [111,112]. For example, acetophenone could be almost completely converted into (*R*)-1-phenylethanol in less than 2 h, leading up to 95% ee, the rate of which was considerably faster than in the HCOONa–Et₃N azeotrope or *i*PrOH, as shown in Scheme 14. Extended application of Rh-(*R,R*)-TsCYDN is seen in the reduction of other ketones including a series of substituted acetophenones and heteroaryl ketones, which afforded high conversions with 77–99% ee's within 5–60 min reaction times [111]. The catalyst loading could be lowered to 0.1%, with TOF reaching 3500 h⁻¹.

In a related study, the chiral M-CsDPEN [M = Ru, Rh, Ir; CsDPEN = (*R,R,R*)- or (*S,S,S*)-*N*-camphorsulfonyl-1,2-diphenylethylenediamine] catalysts have been shown to be

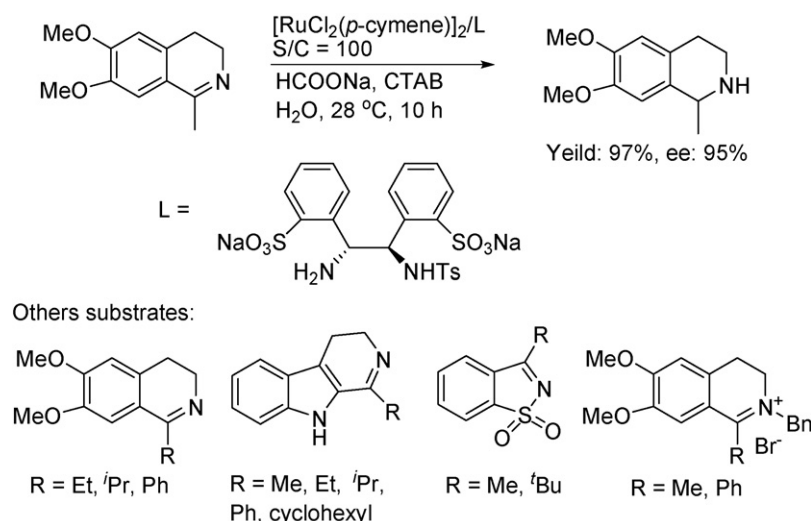
effective for the asymmetric transfer hydrogenation of aryl ketones by formate in neat water. The Ir-(*R,R,R*)-CsDPEN catalyst was shown to be most effective for a wide range of ketones, delivering ee's up to 99% at S/C = 1000 [113].

Water-soluble TsDPEN and derivatives have also been applied to aqueous-phase asymmetric transfer hydrogenation [114]. An interesting recent example is the *o,o'*-disulfonated *N*-tosyl-1,2-diphenylethylene diamine reported by Deng and co-workers, which together with Ru(II) catalyzes transfer hydrogenation of prochiral ketones [115] and cyclic imines/iminiums in water [116]. For instance, as shown in Scheme 15, cyclic imines/iminiums were successfully reduced in high yields (80–99%) and enantioselectivities (75–99% ee) with sodium formate as the hydrogen source. The catalyst so formed dissolves in water and generally necessitates the use of a surfactant like cetyltrimethyl ammonium bromide (CTAB) for substrate transfer.

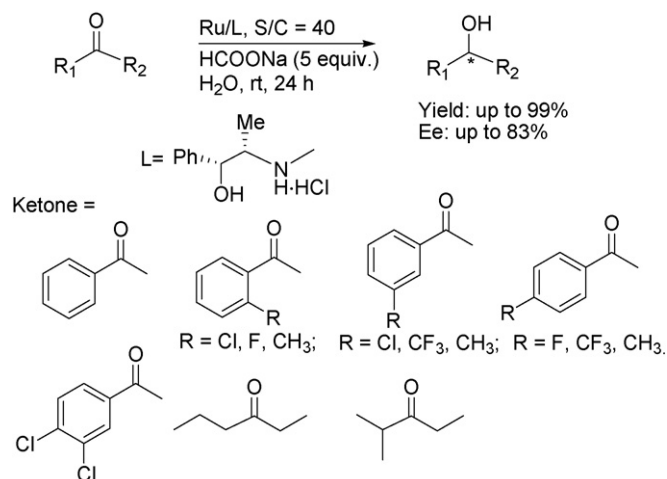
Studies by Xiao and co-workers revealed that, as with aqueous-phase hydrogenation, both the reaction rate and enantioselectivity of the Ru-TsDPEN catalyzed transfer hydrogenation by formate in water were dependent on the solution pH values. Evidence was presented to suggest that two competing catalytic cycles exist during the catalysis, with the importance of each being determined by pH [117].

Apart from TsDPEN and derivatives, ephedrine ((2*R*,3*S*)-3-(methylamino)butan-2-ol), among other amino alcohols, was shown to be an effective ligand for transfer hydrogenation [118]. As shown in Scheme 16, a series of ketones were smoothly reduced to the corresponding alcohol by [RuCl₂(*p*-cymene)]₂ in combination with this ligand in water at room temperature, giving rise to high yields but moderate to good ee's. Related β-amino alcohols have also been studied for similar reduction in water; the enantioselectivities were again moderate to good [119].

Transfer hydrogenation in water by enzyme mimetic catalysis has appeared recently. Ward and co-workers reported the reduction of *p*-methylacetophenone to give *p*-tolylethanol with



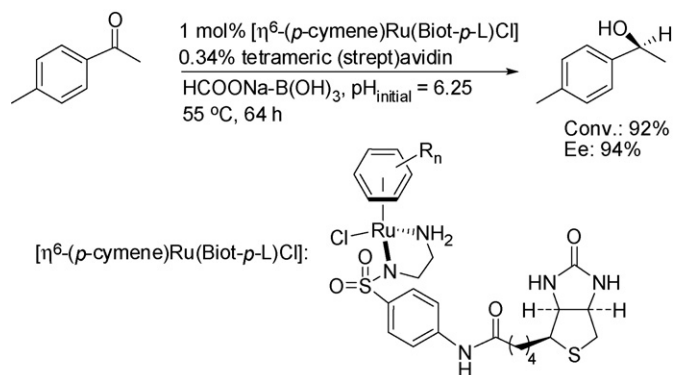
Scheme 15.



Scheme 16.

excellent ee by HCOONa, using an artificial metalloenzyme as catalyst, *i.e.* $[\eta^6\text{-}(p\text{-cymene})\text{Ru}(\text{Biot-}p\text{-L})\text{Cl}]$ immobilized inside of (strept)avidin in a buffered solution (Scheme 17) [120]. It is noted that the Ru(II) center contains no chiral ligand; the observed chiral induction arises from the surrounding enzyme.

Supported TsDPEN has been synthesized for transfer hydrogenation, aiming at easy catalyst and product separation. Xiao and co-workers immobilized TsDPEN on poly(ethylene glycol) (PEG) and initially applied the resulting PEG-TsDPEN ligand to Ru(II)-catalyzed asymmetric reduction of aromatic ketones by HCOOH–NEt₃. However, it was found that catalyst recycle was only possible on the addition of water [121]. Intrigued by the observation, the authors tested the ligand in neat water and found that Ru-(PEG-TsDPEN) was highly effective for asym-

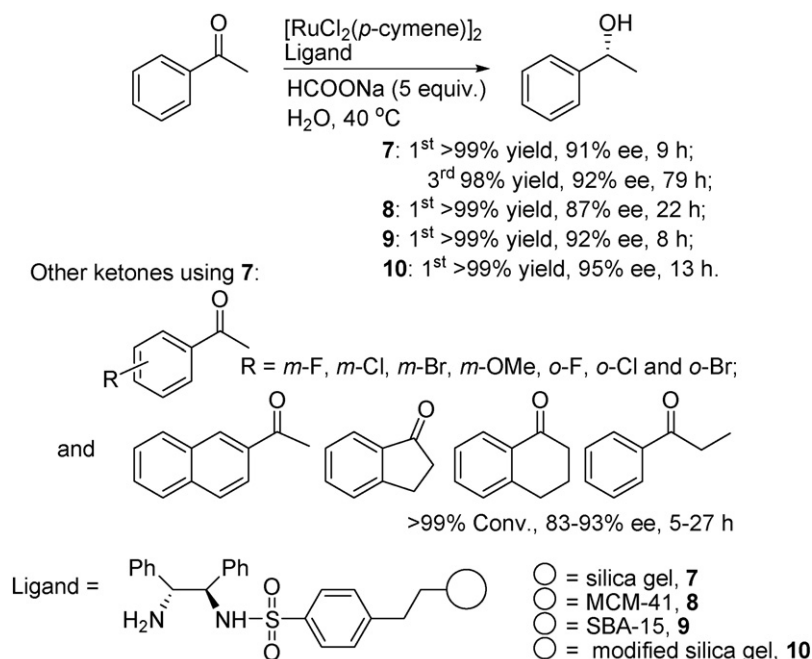


Scheme 17.

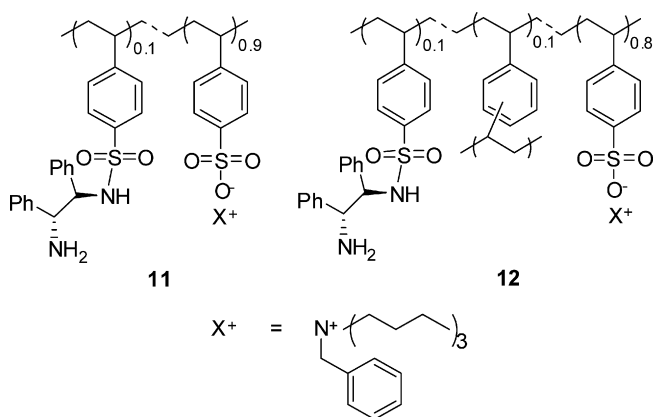
metric hydrogenation of ketones by HCOONa, affording almost complete reactions with >91% ee's at 22–40 °C in 1–36 h. The catalyst was recycled more than 10 times without compromising the ee's [122].

Deng and co-workers developed silica gel, MCM41 and SBA15-supported TsDPEN, and have demonstrated the applicability of these ligands in Ru(II)-catalyzed asymmetric reduction of ketones in water (Scheme 18) [123,124]. Among the catalysts formed, Ru-7 exhibited a high catalytic activity, excellent enantioselectivity and high recyclability with or without additives; the catalysts Ru-8 [123,124] and Ru-10 [124] appeared to be less efficient.

Polymer-supported chiral sulfonamides (11 and 12) containing sulfonated groups and quaternary ammonium salts are also efficient for asymmetric transfer hydrogenation of aromatic ketones in water, showing high conversions and enantioselectivities coupled with easy catalyst recycle without loss of catalytic activities [125].



Scheme 18.

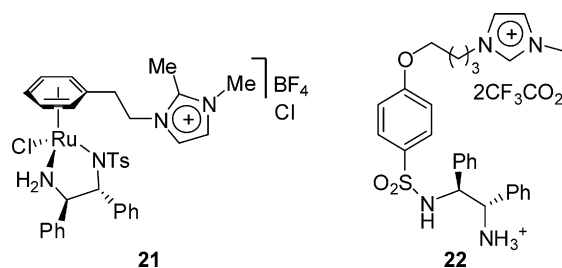


Enantioselective hydrogenation performed in ILs has also received growing attention in recent years, a main purpose being again for recovery and reuse of the expensive chiral catalysts. Chauvin and co-workers first reported that $[\text{Ru}(\text{COD})(-)\text{-DIOP}]\text{PF}_6$ (DIOP = 2,2-dimethyl-4,5-bis((diphenylphosphino)methyl)-1,3-dioxolane), dissolved in $[\text{bmim}]\text{SbF}_6/\text{PrOH}$ (3/8, v/v), catalyzed the asymmetric hydrogenation of α -acetamidocinnamic acid to give (*S*)-phenylalanine in 64% ee; no mention of catalyst recycle was made, however [65]. Following this, asymmetric hydrogenation catalyzed by classical Ru and Rh catalysts of a variety of substrates, ranging from aromatic ketones [126–129], β -ketoesters [130–134], imines [135,136], and enamides [134,137,138] to α -substituted amido cinnamates/cinnamic acids [139,140], have been successfully carried out in ILs, in most cases with catalyst recovery and recycles being demonstrated. Some examples are shown in Table 1. For instance, the optically active Ru-BINAP catalyzed hydrogenation of acetophenone in $[\text{BP}][\text{CB}_{10}\text{H}_{12}]$ afforded 99.1% ee with TOF of 239 h^{-1} under 12 bar H_2 at 50°C for 12 h (Table 1, entry 2). Under the same conditions, acetophenone was readily converted to the corresponding alcohol by the rhodacarborane (*closo*-1,3- $\{\mu$ -(η^2 -3- $\text{CH}_2=\text{CHCH}_2\text{CH}_2$)-3-H-3- PPh_3 -3,1,2- $\text{RhC}_2\text{B}_9\text{H}_{10}$) catalyst in 97.3% ee with TOF of 194 h^{-1} [126]. Similarly, the bisphosphonic acid-functionalized $[\text{Ru}\text{-}\mathbf{13}\text{-}(S,S)\text{-DPEN}]\text{Cl}_2$ catalyzed the asymmetric hydrogenation of aromatic ketones in various imidazolium ILs and isopropanol mixtures, allowing for quantitative yield with up to 98.7% ee [127]. A series of similar ligands in combination with Ru complexes were used to catalyze the asymmetric reduction of β -keto esters in ILs, providing complete conversion with excellent ee's (up to 99.3%), with possible catalyst recycling by simple extraction of product in most cases [130–132].

In a report by Feng and co-workers, seven classes of diphosphines were employed as ligands in combination with $[\text{Rh}(\text{NBD})_2]\text{BF}_4$ to catalyze the hydrogenation of enamides. Some were effective while others not [138]. Ligand **16** was shown to be the best in catalysis; when the reaction was carried out in four different imidazolium ILs in conjunction with water as a co-solvent, it afforded high conversions and ee's (e.g. entry 11, Table 1), which were similar to or higher than those obtained in MeOH. Furthermore, the catalyst could be reused to give >10,000 turnover numbers without significant loss of activity.

The enantioselective hydrogenation of the imine *N*-(1-phenylethylidene)aniline by a cationic iridium complex with chiral phosphinoxazoline ligand proceeded readily in $[\text{emim}][\text{BARF}]$ (entry 10, Table 1). The product was extracted from the IL solution by using scCO_2 without contamination of the IL or catalyst [135]. The presence of CO_2 was beneficial for efficient hydrogenation, probably due to an increased H_2 solubility and/or reduced viscosity of the reaction solution.

Enantioselective transfer hydrogenation in ILs has also appeared in the recent literature. The scarcity of this kind reaction in ILs may to some extent be due to the fact that the hydrogen source and solvent in these reactions are often the same, with other solvents less explored in comparison with hydrogenation reactions. Dyson and Geldbach recently reported the asymmetric hydrogenation of acetophenone by 2-propanol and the $\text{HCOOH}\text{-Et}_3\text{N}$ azeotrope in the IL $[\text{bdmim}]\text{PF}_6$, which can phase-separate from 2-propanol and appears stable toward base. A modified Noyori–Ikariya catalyst was used; the ionic tag fixed the catalyst in the IL phase (ligand **21**) [141]. A quantitative conversion and excellent ee with successful catalyst recycle (>99%) were afforded by using $\text{HCOOH}\text{-Et}_3\text{N}$ as hydrogen source, while it was less effective by using 2-propanol.



A similar modification, on the tosyl part of the diamine ligand, led to the ligand **22**, which, in combination with $[\text{RuCl}_2(\text{benzene})]_2$, effected the transfer reduction of acetophenone by $\text{HCOOH}\text{-Et}_3\text{N}$ in the IL $[\text{bmim}]\text{PF}_6$ [142]. A 98% conversion and 92% ee were obtained, and catalyst recycling without any loss in both activity and enantioselectivity could be carried out up to a third run.

ScCO_2 has been used as solvent for a number of enantioselective hydrogenations [12]. To some extent, catalyst solubility, especially that of metal complexes, has been a problem [143]. As aforementioned, to overcome this problem perfluoroalkyl-modified ligands have been used, a recent example of which is shown in Scheme 19 [144]. The hydrogenation of methyl-2-acetamidoacrylate by the Ru-perfluoroalkyl-BINAP in scCO_2 , in the presence of a fluorinated co-solvent 1,1,1,3,3,3-hexafluoro-2-propanol or trifluorotoluene, proceeded to afford 63–74% ee's, which were higher than those using unmodified BINAP.

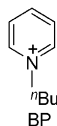
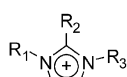
$\text{Ru}\text{-}[\textit{p}\text{-OCF}_3\text{-BINAP}]$, a modified BINAP with *p*- OCF_3 -substitution on the phenyl groups in BINAP, was demonstrated to exhibit enough solubility in dense CO_2 and to be an active catalyst for the enantioselective hydrogenation of tiglic acid in CO_2 with trace methanol as a co-solvent [145].

Table 1
Asymmetric hydrogenation in ionic liquids

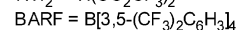
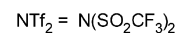
Entry	Catalyst	Solvent	Sub.	S/C	P (bar)	ee (%) ^a	Ref.
1	Ru/(R)-BINAP	[Omim]BF ₄	a	1000	12	97.3	[126]
2	Ru/(R)-BINAP	[BP][CB ₁₀ H ₁₂]	a	1000	12	99.1	[126]
3	Ru/(R)- 13 -[(S,S)-DPEN]Cl ₂	[Bmim]BF ₄ /iPrOH	c	1000	48	98.7	[127]
4	Ru/(R)- 13 -[(S,S)-DPEN]Cl ₂	[Bmim]PF ₆ /iPrOH	c	1000	48	93.7	[127]
5	Ru/(R)- 13 -[(S,S)-DPEN]Cl ₂	[DMPim]NTf ₂ /iPrOH	c	1000	48	98.1	[127]
6	Ru/(R)- 13 -[(S,S)-DPEN]Cl ₂	[BDMim]BF ₄ /iPrOH	c	1000	48	98.3	[127]
7	Ru/TPPTS/ 14	[Bmim][p-CH ₃ C ₆ H ₄ SO ₃]	b	112	50	80.6	[128]
8	Ru/(S)-BINAP	[Bmim]PF ₆ /EtOH-CH ₂ Cl ₂	e	100	12	95.0	[133]
9	Rh/ 18	[Bmim]PF ₆ /H ₂ O	f	500	5	96.0	[134]
10	[Ir(COD)/ 15]PF ₆	[Emim][BARF]	h	250	30	78.0	[135]
11	Rh/ 16	[Omim]BF ₄ /H ₂ O	g	200	1	>99	[138]
12	[Ir(COD)Cl] ₂ / 17	[C ₁₀ mim]NTf ₂	i	25	40	86	[136]
13	Ru/ 20 /Me ₃ OBf ₄	[Bmim]SbF ₆ /iPrOH	j	100	1	97.0	[137]
14	Rh/ 18	[Emim]OTf	k	25	4	89 ^b	[140]
15	Rh/ 19	[Bmim]BF ₄	f	100	5	92 ^c	[139]
16	Rh/ 19	[Bmim]BF ₄	g	100	5	87	[139]

ILs

Cation:



Anion:

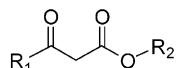


[emim]: R₁ = Me, R₂ = H, R₃ = Et;
 [bmim]: R₁ = Me, R₂ = H, R₃ = *n*-Bu;
 [omim]: R₁ = Me, R₂ = H, R₃ = *n*-Oct;
 [DMPim]: R₁ = Me, R₂ = Me, R₃ = *n*-Pr;
 [BDMim]: R₁ = Me, R₂ = Me, R₃ = *n*-Bu;
 [C₁₀mim]: R₁ = Me, R₂ = H, R₃ = *n*-C₁₀H₂₁.

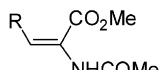
Substrates



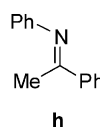
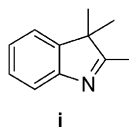
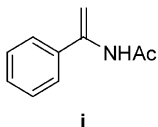
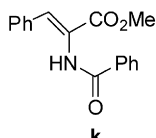
a R₁ = Ph, R₂ = Me;
b R₁ = Ph, R₂ = *n*-Pr;
c R₁ = 4'-*t*-Bu-Ph, R₂ = Me.



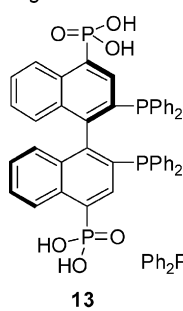
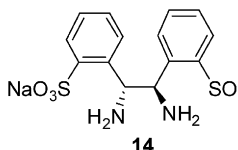
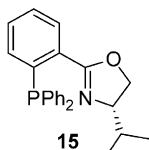
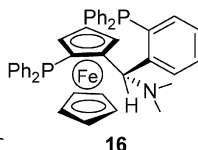
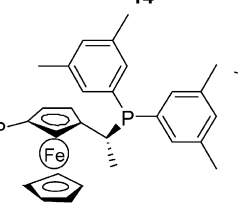
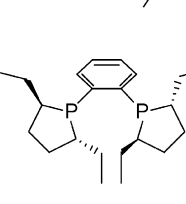
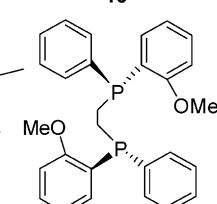
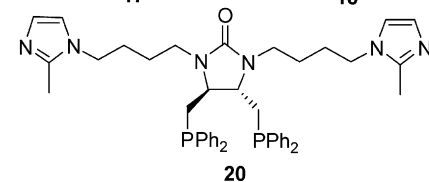
d R₁ = R₂ = Me;
e R₁ = CH₂Cl, R₂ = Et.

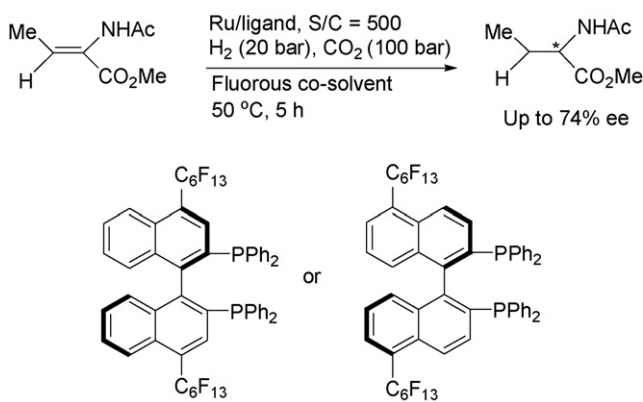


f R = H
g R = CH₃

**h****i****j****k**

Ligands

**13****14****15****16****17****18****19****20**^a At >99% conv.^b 95% conv.^c 90% conv.



Scheme 19.

In related studies but using monodentate ligands, Hope and co-workers found that chiral perfluoroalkylated monophosphorus ligands were highly effective in rhodium-catalyzed asymmetric hydrogenation of dimethyl itaconate in CH_2Cl_2 , with the perfluoroalkyl substituents exerting a considerable influence on the enantioselectivities of the catalyst; however, in scCO_2 , even in the presence of CO_2 -philic fluorinated anions, activities as well as enantioselectivities were modest [146].

2.2. Hydroformylation and carbonylation

Hydroformylation, the addition of CO and H_2 to an alkene, is one of the most important industrial catalytic processes. The reaction is totally atom-efficient, with all the starting atoms being incorporated into the product, forms a new C–C bond and introduces a carbonyl functional group into the original carbon chain. There are a number of catalysts for the reaction, with those based on cobalt and rhodium being by far most successful under either homogeneous or aqueous biphasic conditions [147].

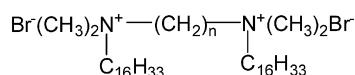
The well-known Ruhrchemie/Rhône-Poulenc process uses an aqueous biphasic system and a water-soluble Rh/TPPTS catalyst to hydroformylate short-chain olefins, with feasible catalyst recycle. The process cannot be applied to long-chain (≥ 6) olefins, however, which are not soluble enough in water to make an effective reaction. The search for more effective, aqueous catalytic systems for higher olefins remains active. The investigation has also been extended to other non-conventional solvents such as ILs, scCO_2 and fluororous fluids. Earlier research in this area has been well documented [12,14,16,147,148]. Herein, some studies reported in the past a few years are presented.

The hydroformylation of higher alkenes using a combination of Ru or Co complexes with water-soluble phosphorous ligands such as TPPTS, TPPMS and their derivatives in aqueous solution has been extensively investigated [149–155]. $\text{CoCl}_2(\text{TPPTS})_2$ was used to catalyze the hydroformylation of 1-hexene in an aqueous biphasic medium to give great than 90% conversion with 68% selectivity and *n/iso* ratio of 3.0 for aldehydes at 100 °C and CO/H_2 pressure of 90 bar [149]. The water-soluble ruthenium complex $\text{H}_2\text{Ru}(\text{CO})(\text{TPPMS})_3$ was shown

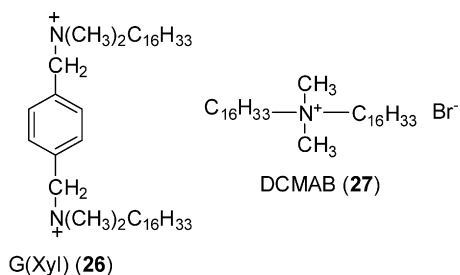
to be an efficient catalyst precursor for the aqueous-biphasic hydroformylation of terminal, substituted and cyclic alkenes, and their mixtures. Thus, 1-hexene was readily hydroformylated to give 90% aldehyde composed of 60% *n*-heptanal and 30% branched aldehydes, 2-methylhexanal and 2-ethylpentanal [150]. Further studies revealed that the catalyst tends to isomerize the C=C bonds from the terminal to the internal positions; nevertheless, this could be suppressed by using a higher CO/H_2 pressure [151]. The selectivity was influenced to some extent by ionic strength and temperature. For instance, the hydroformylation of 4-penten-1-ol in water using $\text{HRu}(\text{CO})(\text{TPPTS})_3$ as a catalyst preferred to yield a linear product 6-hydroxy-hexan-1-al with a decrease of temperature, but 2-hydroxy-3-methyltetrahydropyran derived from the branched aldehyde with an increase of the ionic strength [152]. The water-soluble hydride complex $[\text{HRu}(\text{CO})(\text{CH}_3\text{CN})(\text{TPPTS})_3]\text{BF}_4$ was synthesized and used as a catalyst precursor for aqueous biphasic (water/*n*-heptane) hydroformylation of 1-hexene, 2,3-dimethyl-1-butene, styrene, allylbenzene, cyclohexene and their mixture; the catalyst was shown to tolerate thiophene and could be recycled [153]. The electronic and steric properties of the aromatic rings in the phosphine ligands impact on the activity and selectivity as well. For instance, among Rh-TPPTS, Rh-(2-MOTPPTS) and Rh-(4-MOTPPTS) (*n*-MOTPPTS is tris[*n*-methoxy-3-(sodium sulfonato)phenyl] phosphine), the latter two exhibited a lower activity and selectivity for aldehydes in the hydroformylation of 1-dodecene in the aqueous phase [154].

The water-soluble rhodium complex $[\text{Rh}(\mu\text{-Pz})(\text{CO})(\text{TPPMS})_2]$ (Pz = pyrazolate) was also explored as a catalyst for the hydroformylation of 1-hexene and styrene in a water/heptane biphasic system, resulting in isomerization first and then formation of aldehydes with a low *n/iso* ratio from 1-hexene, and a mixture of 2-phenylpropanal and 3-phenylpropanal (90/10 after 1 h with 90% conversion) from styrene, respectively. The catalyst was stable enough to be recycled [156].

Efforts have been made to overcome the mass transfer problems encountered in biphasic catalysis by using additives, such as surfactants, co-solvents or amphiphilic ligands. Surfactants decrease interfacial tension and can form small aggregates above the critical micellar concentration (CMC), thus accelerating a reaction by enlarging interfacial areas. For example, the hydroformylation of 1-hexene, catalyzed by $\text{RuCl}(\text{CO})(\text{TPPTS})\text{-BISBIS}$ (BISBIS = sulfonated 1,1'-bis(diphenylphosphino methyl)-2,2'-biphenyl) in an organic/aqueous biphasic system, could be greatly speeded up by the addition of the cationic surfactant CTAB to afford TOF of 740 h^{-1} and 96.5% of regioselectivity for the linear aldehyde under optimum conditions [157,158]. Studies also showed that mixed micelles were better in achieving a higher conversion and higher regioselectivity in the hydroformylation of 1-dodecene by $\text{RuCl}(\text{CO})(\text{TPPTS})_2$ [159]. The surfactant structure also had an important effect on the reaction rate, the order of rate promotion being DCMAB (27) > G(Eth) (23) \approx G(But) (24) \approx G(Hex) (25) \approx G(Xyl) (26) > CTAB [160].



$n = 2$, G(Eth) (**23**); $n = 4$, G(But) (**24**) and $n = 6$, G(Hex) (**25**)



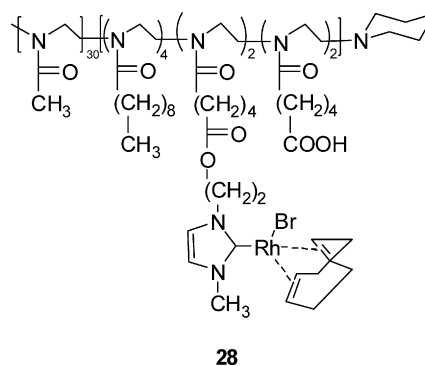
The effect of surfactants on the reaction rate can be substrate-dependent. Thus, in the case of the hydroformylation of terpenes catalyzed by Ru/TPPTS in water/toluene, addition of cetyltrimethylammonium chloride (CTAC) was necessary for the reaction of myrcene to take place; but this promotion was much less pronounced for limonene and CTAC turned out to be an inhibitor for camphene [161].

The disulfonated cetyldiphenyl phosphine $n\text{-C}_{16}\text{H}_{33}\text{P}(m\text{-C}_6\text{H}_4\text{SO}_3\text{Na})_2$ (CDPPDS) was reported to be able to function as both a surfactant and a ligand simultaneously in the hydroformylation of higher olefins [162]. Thus, 1-dodecene was hydroformylated in water/toluene (3:1, v/v) under mild conditions (olefin/Ru = 2500, CO/H₂ = 1, $P(\text{CO}/\text{H}_2) = 15$ bar, L/Ru = 10, 4 h reaction time) to give 30.7% conversion with TOF of 188 h⁻¹ and *n*/*iso* of 3.7 under Ru-CDPPDS-TPPTS catalysis (CDPPDS/TPPTS = 1/6). This compares favourably with those obtained with Ru-TPPTS without CDPPDS, 20.0% conversion with TOF of 125 h⁻¹ and *n*/*iso* of 3.4. Under identical conditions, the same reaction yielded a 52.5% conversion with a TOF of 328 h⁻¹ and *n*/*iso* of 2.8 by using Ru-CDPPDS alone.

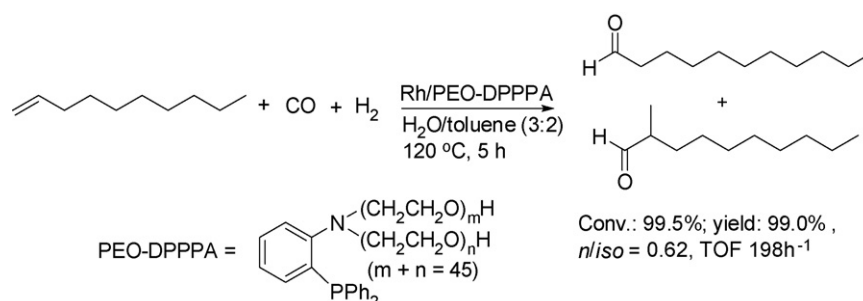
Another approach to creating micellar catalysis is to use non-ionic surfactants. A good example is seen in some water-soluble polymer ligands that display an inverse temperature-dependency of solubility in water. In this context, Jin and co-workers applied the concept of “thermoregulated phase-transfer catalysis” (TRPTC) to aqueous–organic biphasic hydroformylation of higher olefins [163,164]. The key point is that by increasing the temperature, the catalyst is firstly transferred to the organic phase where it catalyzes a reaction and then, at a lower temperature, it moves back to the aqueous phase where it is separated from the product. As shown in Scheme 20, the water-soluble lig-

and PEO-DPPPA in combination with RhCl₃·3H₂O catalyzed the hydroformylation of 1-decene, affording 99% yield of the aldehyde under the conditions of 120 °C, 50 bar (CO/H₂ = 1), P/Ru = 4 and *S*/*C* = 1000 in 5 h. Recycling tests showed that both the conversion and yield of aldehyde were still higher than 94% even after 20 times of catalyst reuse. At a *S*/*C* ratio of 26600, the reaction still proceeded well to give 79.8% conversion and 79.3% yield for aldehyde with a *n*/*iso* of 0.42 and TOF of 4218 h⁻¹ [163].

A similar study by Weberskirch and co-workers described that the immobilized Rh-carbene complex on an amphiphilic block co-polymer (**28**) was an efficient catalyst for the hydroformylation of 1-octene, exhibiting up to 2360 h⁻¹ TOF under aqueous/organic two-phase conditions in four consecutive cycles [165]. A catalyst derived from the sulfonated thioetheralkylphosphine ligand PPh₂(CH₂)₂S(CH₂)_nSO₃Na, ($n = 2, 3$) and [Rh(OAc)₂]₂ showed high activity for the hydroformylation of 1-dodecene at *S*/*C* = 10,000 in a two-phase system at 60 bar CO/H₂ and 120 °C, achieving TONs > 50,000 without using a surfactant and TONs of *ca.* 65,000 in the presence of the commercially available polyoxyethylene–polyoxypropylene block co-polymer Synperonics [166].



As a mass transfer promoter, randomly methylated β-cyclodextrin (RAME-β-CD) was effective for the hydroformylation of higher olefins, although the *n*/*iso* ratio of product was lower (1.8 versus 2.8 without cyclodextrin) [167]. This was explained to be due to the formation of an inclusion complex between RAME-β-CD and the ligand used, TPPTS. In contrast, modified α-cyclodextrins, which could not form inclusion complex because of their smaller cavities, have been demonstrated to be excellent mass transfer promoters for the aqueous catalytic hydroformylation of higher

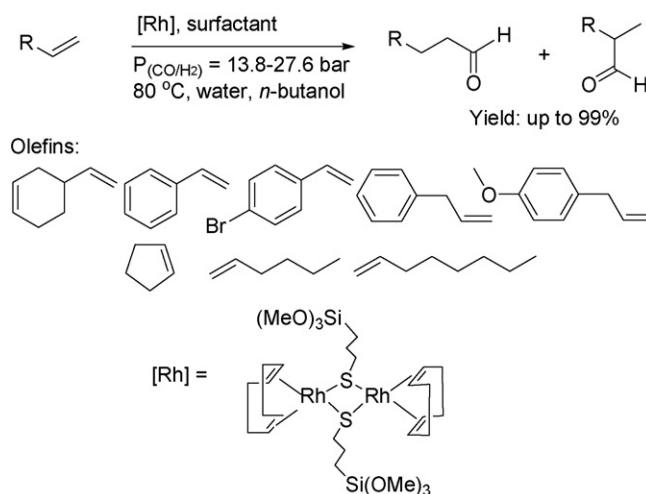


Scheme 20.

olefins [168–170]. For example, 1-octene was successfully hydroformylated by Rh-TPPTS in the presence of methylated- α -cyclodextrin (RAME- α -CD) under the conditions of 50 bar CO/H₂ (1:1) at 80 °C for 6 h in an aqueous biphasic system to afford 96% conversion with 99% selectivity for aldehyde with *n*/*iso* ratio of 3.0. Under the same conditions, the reaction only gave a 3% conversion with 33% selectivity and *n*/*iso* of 2.8 without RAME- α -CD [168]. α -CD derivatives bearing 2-hydroxy-3-trimethylammoniumpropyl groups were also shown to promote mass transfer in the hydroformylation of higher olefins in biphasic systems, providing enhanced reactivity, selectivity for aldehyde, and a significantly increased *n*/*iso* ratio, e.g. up to 5.4 for 1-decene [170]. ¹H and ³¹P NMR studies suggested that the increased *n*/*iso* ratio was due to *in situ* formation of new supermolecular catalytic species by ion-exchange between the ligand and cationic α -CD. On the other hand, when combined with a bidentate ligand, sulfonated Xantphos, RAME- β -CD could also provide enhanced activity and *n*/*iso* ratio, for example, allowing for 90% conversion with >99% selectivity and *n*/*iso* ratio of 20 for 1-octene. In this case, RAME- α -CD led to a 74% conversion, 99% selectivity and *n*/*iso* ratio of 33. For comparison, Rh-sulfonated Xantphos alone afforded a 19% conversion, 94% selectivity and *n*/*iso* ratio of 14 [169]. The reason for the increased *n*/*iso* ratio was thought to arise from the steric constraints imposed by the bidentate ligand and the CDs, and from interactions between the two groups, which were too weak to induce dissociation of ligand from the complex. Such dissociation resulted in the lower *n*/*iso* ratios in the case of TPPTS or TPPMS, as aforementioned. More recently, Monflier and co-workers reported the heptakis(2,3-di-*O*-methyl-6-sulfopropyl) β -CD to be more efficient than the randomly methylated β -CD for the biphasic hydroformylation of olefins [171]. Studies into the interaction between α - or β -CD and sulfonated diphosphines by van Leeuwen and co-workers showed that the flexibility of the diphosphine backbone had an effect on both the activity and selectivity of hydroformylation of 1-decene [172].

Studies by Blum and co-workers suggest that microemulsion [173], which was found to be superior to emulsion in hydrogenation [174], can be used in hydroformylation of higher olefins [175–177]. Depending on the amount of surfactant, microemulsion could create a monophasic or pseudo-homogeneous system when a high proportion of surfactant is used, or a ternary mixture when a suitable, minimum amount of surfactant is present. As shown in Scheme 21, aqueous hydroformylation of various hydrophobic alkenes was successfully performed in a three-phase microemulsion/sol–gel system, catalyzed by a rhodium catalyst in the presence of *N*-dodecyl-*N*-(2-hydroxyethyl)-*N,N*-dimethylammonium bromide as surfactant and *n*-butanol as a co-solvent, affording 62–99% aldehydes [177].

Internal olefins can be converted into linear aldehydes by a suitable catalyst. Beller and co-workers described for the first time the hydroformylation of internal olefins catalyzed by Rh-BINAS (BINAS = sulfonated 2,2'-bis(diphenylphosphinomethyl)-1,1'-binaphthalene) in an aqueous biphasic system, to give linear aldehydes with significantly



Scheme 21.

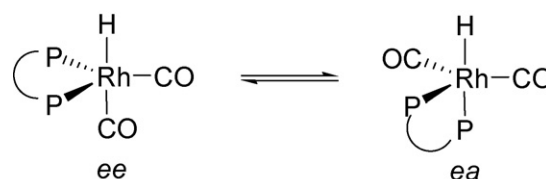
higher regioselectivities (*n*/*iso* > 99:1), compared to similar catalysts in organic solvents [178]. The control of pH and CO partial pressure was shown to be important for a successful reaction in this case.

Hydroformylation of higher olefins by supported aqueous-phase catalyst (SAPC) has continued [179–182]. In this system, the catalyst is immobilized into a thin water layer adhered to the pores of a porous solid, e.g. silica. It combines potentially the advantages of both heterogeneous and homogeneous catalysis. As there is a large interfacial area, catalyst–substrate contact is facilitated, which could result in a relatively high conversion rate of alkenes. Catalyst recycle is also feasible.

As abovementioned, higher olefins have poor solubility in water, which hampers their hydroformylation in aqueous medium. ILs, showing higher solubilities for these olefins, could be used to replace the aqueous phase in biphasic hydroformylation, and hence was extensively studied in this regard [12,14,8]. From 2003 onwards, however, only a few publications have appeared. They are presented in the follow section.

Hydroformylation of 1-octene was performed using a classical rhodium precursor in [bmim]PF₆ [183]. The metal complex was formed by dissolving Rh(acac)(CO)₂ in [bmim]PF₆ in the presence of 4 equiv. of sulfonated Xantphos under different pressures. *In vivo* high pressure (HP) IR and NMR revealed that the complex was present in the IL in a dynamic equilibrium between the *ee* and *ea* configurations, as shown in Scheme 22. The reaction was influenced by temperature and syngas pressure, but not related to the hydrogen partial pressure.

Interestingly, the biphasic hydroformylation of 1-hexene by Rh-TPPTI (TPPTI = tri(*m*-sulfonyl)triphenyl phosphine-1,2-



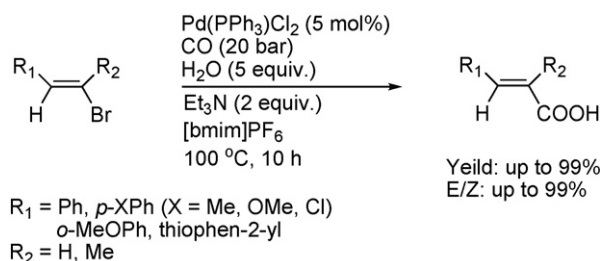
Scheme 22.

dimethyl-3-butyl-imidazolium) in [bmim]BF₄, [bmim]PF₆ or [bdmim]PF₆ was shown to be one order of magnitude slower than that observed with the conventional Rh-PPh₃ catalyst in toluene, although HP NMR studies indicated that the solution structure of HRh(¹³CO)(TPPTS)₃ in [bmim]BF₄ was similar to that of HRh(¹³CO)(PPh₃)₃ in toluene-d⁸ [184]. On the other hand, HRh(CO)(TPPTS)₃ was reported to be more active and selective for hydroformylation of 1-hexene in the IL [Rmim][*p*-CH₃C₆H₄SO₃] (R = *n*-butyl, *n*-octyl, *n*-dodecyl and *n*-cetyl) than in [bmim]BF₄/PF₆, allowing for TOF as high as 2736 h⁻¹ [185].

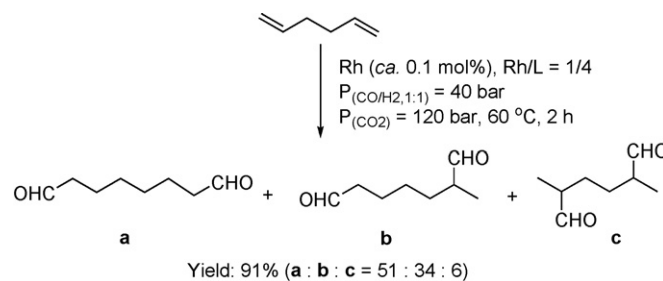
Rhodium catalysts in supported IL phase (SILP) were reported by Wasserscheid and co-workers [186–188] and Yuan and co-workers [189] to exhibit homogeneous nature, and be more regioselective and active than the IL-free analogues. The SILP catalyst, Rh-sulfonated Xantphos in [bmim]X (X = PF₆ or *n*-C₈H₁₇OSO₃) on silica, was regioselective, giving up to 96% linear product in the hydroformylation of propene; but the catalyst suffered from deactivation after a prolonged use [186]. However, when using partly dehydroxylated instead of non-dehydroxylated silica, the same catalyst in [bmim][*n*-C₈H₁₇OSO₃] remained active, highly selective and stable (up to 60 h) [187]. SILP catalysis has recently been successfully applied to a continuous gas-phase methanol carbonylation in a fixed-bed reactor [190]. The Monsanto-type catalyst combined with SILP, *i.e.* [Rh(CO)₂I₂]-[bmim]I-SiO₂, was reported to show an excellent activity and selectivity towards acetyl products.

Carbonylation of olefins and aryl halides with nucleophiles in ILs to give the corresponding esters or amides has also been reported, with palladium being used as catalyst in most cases [191–196]; examples include the Pd-catalyzed hydroethoxycarbonylation of styrene [194], and Rh-catalyzed hydroaminomethylation of long-chain olefins with secondary amines [195]. A Pd-catalyzed hydroxycarbonylation of vinyl bromides (*E/Z* ≥ 5:1) led to the corresponding α,β-unsaturated carboxylic acids in moderate to very good yield (up to 99%) with excellent stereoselectivity (*E/Z* up to 99:1) in [bmim]PF₆, as shown in Scheme 23 [196].

Hydroformylation could benefit from an IL-scCO₂ system, as both the reagents and products have good solubilities in the mobile scCO₂ phase while the metal catalysts could be retained in a stationary IL phase throughout the reaction. This allows for easy catalyst/product separation and also for continuous flow



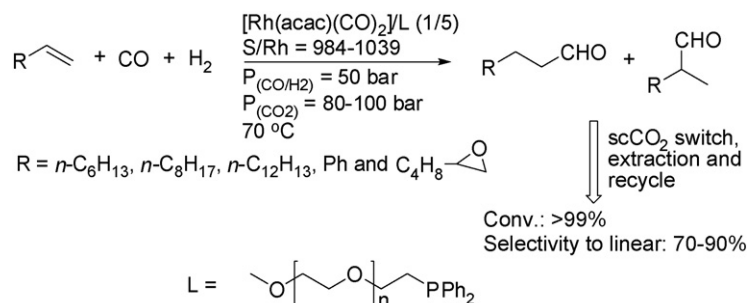
Scheme 23.



Scheme 24.

operation, as demonstrated by Cole-Hamilton and co-workers [197]. In this context, it is noted that scCO₂ not only acts as a transport vector for both substrates and products, but also helps reduce the mass transfer problem by increasing the reagent solubility in an IL phase, which also reduces the viscosity of IL. In the work of Cole-Hamilton, Rh-catalyzed hydroformylation of 1-octene in a continuous flow system, [octmim]NTf₂/scCO₂, was shown to be highly efficient, affording TOF as high as 500 h⁻¹ with rhodium leaching into the product stream as low as 0.012 ppm [197].

Hydroformylation of olefins has also been carried out in scCO₂ or fluorinated solvents, again for the purpose of catalyst recovery. CO₂-philic or fluorinated ligands are often used to improve the catalyst solubility. In recent examples, hydroformylation of dienes to dialdehydes by rhodium in conjunction with fluorinated ligands in scCO₂ was reported [198,199]. Scheme 24 shows the hydroformylation of 1,5-hexadiene by Rh-P[3,5-(CF₃)₂C₆H₃]₃ to give dialdehydes with a high yield of 91%, albeit with poor regioselectivity. However, both of the yield and selectivity in scCO₂ were higher than in toluene [198]. The same trend was observed for 1,7-octadiene.

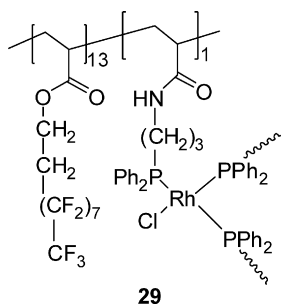


Scheme 25.

Leitner and co-workers reported a sequential catalysis and separation process using scCO_2 to switch phase by making use of its polarity and volatility [200]. A cartridge catalyst was dissolved in the reaction mixture during the reaction, and precipitated quantitatively at the separation stage by introducing scCO_2 to induce phase switch and mass separation. By using this technique, as shown in Scheme 25, a set of structurally diverse olefins were smoothly hydroformylated in sequence in a total of eight cycles of catalyst reuse, affording complete conversion for each substrate with up to 90% selectivity in favour of linear aldehyde and 86–100% catalyst recovery in each cycle. The rhodium cartridge catalyst was based on a PEG-modified phosphine ligand.

CO_2 -expanded liquid (CXL) is another application of CO_2 in catalytic reactions including hydroformylation. In this system, CO_2 is condensed into an organic solvent, lowering the solvent polarity and thereby precipitating the catalyst. Hydroformylation can be effected in a CXL by using the unmodified $\text{Rh}(\text{acac})(\text{CO})_2$ as catalyst [201].

For facile product–catalyst separation, hydroformylation by supported catalysts in scCO_2 was also investigated [202–206]. Thus, heterogeneous rhodium [202] and platinum/tin [203] catalysts on silica were employed to catalyze the hydroformylation of 1-hexene in scCO_2 . The catalysts were shown to be active, selective and stable for the formation of heptanal, with the latter being better in regioselectivity for the linear aldehyde. Polymer-supported catalysts were also explored. The Rh catalyst **29** was shown by Akgerman and coworkers to be soluble in scCO_2 , and active for the hydroformylation of styrene affording 100% conversion with 95–100% selectivity for the branched aldehyde at 50–75 °C and 172–241 bar syngas within 24 h [205].



Hydroformylation was the first catalytic reaction to be carried out in the fluororous biphasic system (FBS) and has been extensively studied since [16]. Because the catalysis can be designed to occur under homogeneous conditions at a higher

temperature and the catalyst–product separation can be tailored to occur under biphasic conditions at a lower temperature, FBS offers advantages for homogeneous catalysis. An overview is recently provided by Cole-Hamilton, Hope and co-workers [207]. Scheme 26 shows an example of 1-octene hydroformylation by rhodium associated with the fluororous phosphine $\text{P}(\text{C}_6\text{H}_4\text{-4-OCH}_2\text{C}_7\text{F}_{15})_3$ in a FBS (C_7F_{14} /toluene, 8/5), affording 98% conversion (TOF of 380 h^{-1}) with 97% selectivity in aldehyde ($n/\text{iso} = 2.8$) at 80 °C. The fluororous phase containing the catalyst was recovered at room temperature after the reaction and could be recycled three times without losing activity and selectivity. When performed in perfluoromethylcyclohexane alone, the activity increased (TOF of 1040 h^{-1}) with selectivity and regioselectivity unchanged [208]. The phase behaviour of the fluororous solvent/substrate/product in the FBS system was found to be affected by temperature, substrate concentration and conversion [209].

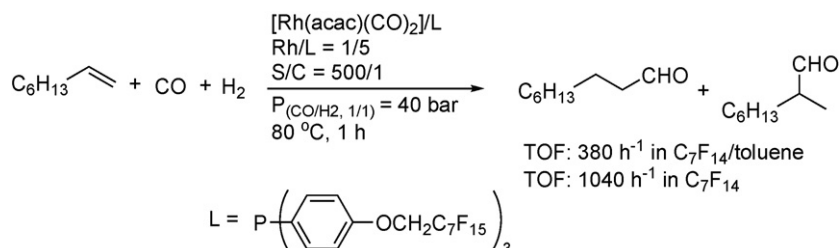
A continuous flow fluororous biphasic system has been developed for hydroformylation of high olefins [210,211]. The system was tested on the hydroformylation of 1-octene, affording conversions up to 70% with n/iso ratio around 12 and successful fluororous catalyst recycling [210]. Efficient stirring was essential for high conversion and minimized alkene isomerization. The separation efficiency was found to be affected by the conversion and the partition of both the product in fluororous phase and the fluororous solvent in an organic phase, but not by the pressure [211].

2.3. Catalytic C–C coupling reactions

Catalytic C–C coupling reactions have become a major area of interest in organic chemistry. The reactions have traditionally been carried out in conventional organic solvents. In the past decade, they have been successfully demonstrated in the alternative media, in order for easy catalyst recovery and minimized environmental impact. In the sections to follow, a range of well-known C–C coupling reactions in the alternative media will be highlighted; these include the transition metal-catalyzed Mizoroki–Heck, Suzuki–Miyaura, Stille, Sonogashira, and Tsuji–Trost reactions.

2.3.1. Heck reactions

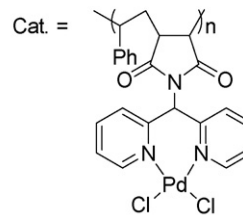
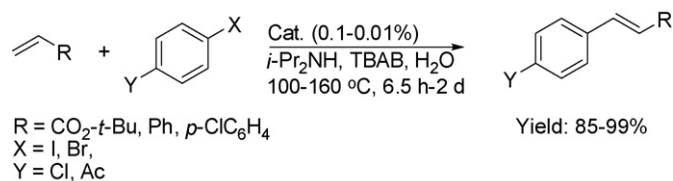
The Mizoroki–Heck reaction, or more frequently the Heck reaction, *i.e.* coupling of aryl or vinyl halides and their derivatives with an olefin, has been widely investigated in the alternative solvents. A recent review by Beleskaya and co-



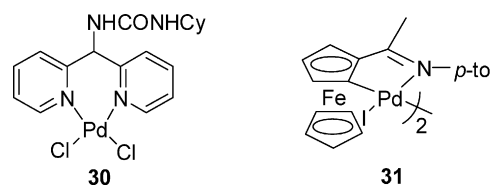
Scheme 26.

workers described the reaction in detail, covering reaction media, substrates, catalytic systems and other reaction conditions [212].

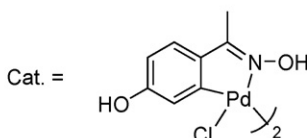
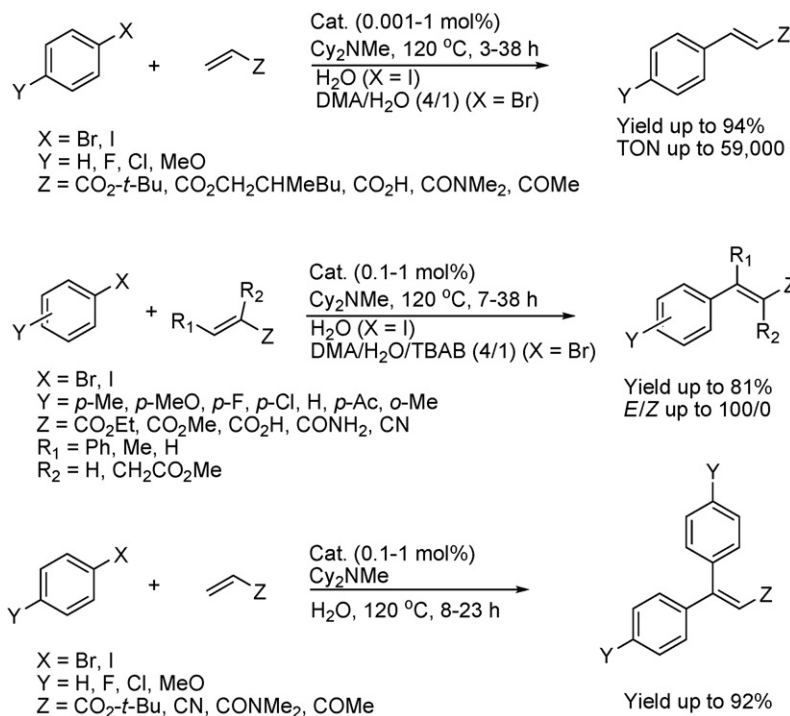
Since the early work of Beletskaya on the Heck reaction in aqueous phase in 1989 [213], a number of publications have appeared. One of the attractive methods for performing the reaction in water is to use phosphine-free or ligand-free catalysts aided by a suitable phase transfer reagent. Two recent examples are seen in the phosphine-free (di-2-pyridyl)methylamine **30** [214] and cyclopalladated ferrocenylimine palladium catalyst **31** [215], which were shown to be effective catalysts for the Heck monoarylation of styrene and acyclic acid derivatives with aryl iodides and bromides in neat water. In the case of the catalyst **31**, however, the presence of an ammonium salt was necessary. When **30** was covalently anchored to a styrene-*alt*-maleic anhydride co-polymer, the supported catalyst showed high activity in the Heck, Suzuki and Sonogashira coupling reactions in neat water [216]. For example, as shown in Scheme 27, *tert*-butyl acrylate or styrenes was successfully coupled with aryl halides in neat water with diisopropylamine as base in the presence of tetra-*n*-butylammonium bromide (TBAB), affording excellent yields with TON as high as 10^4 with the catalyst recyclable. When using MW heating, the reaction was much faster, finishing in 10 min at 100 °C to give complete conversion with 80% yield in the case of styrene coupling with 4-bromoacetophenone. Polymer degradation and palladium leaching was observed, however.



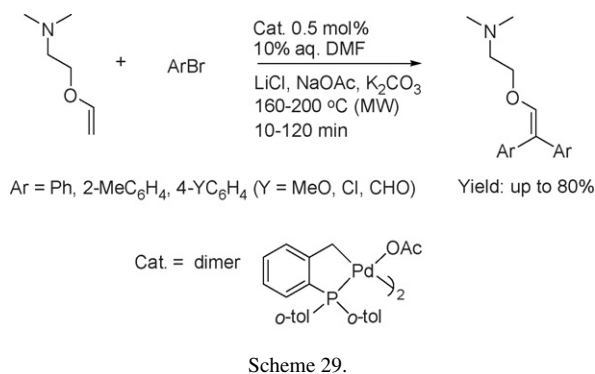
Scheme 27.



The dimeric *p*-hydroxyacetophenone oxime-derived palladacycle described by Nájera and Botella is a very active and robust catalyst for the C–C bond formation reactions, including Heck and Suzuki couplings, in an aqueous phase (Scheme 28). Examples are seen in the synthesis of methoxylated stilbenoids



Scheme 28.



by Heck coupling of styrenes with aryl iodides in aqueous *N,N*-dimethylacetamide (DMA) [217], monoarylation of unsubstituted or β -substituted α,β -unsaturated carbonyl compounds, β,β -diarylation of acrylic derivatives with aromatic iodides or bromides in neat water [218] or aqueous DMA [219], and the synthesis of CNA derivatives or 3-arylpropanoate ester by chemoselective arylation of acrolein diethyl acetal [220]. As shown in Scheme 28, monoarylation and diarylation of α,β -unsaturated compounds catalyzed by the oxime-derived palladacycle was successfully performed in refluxing water or in aqueous DMA under moderate conditions to give high yields [219]. The reaction also proceeded smoothly by Pd(OAc)₂ catalysis without using any ligand under the same conditions, although it was slower in some cases. Under MW heating, the reaction became faster, however.

Hallberg and co-workers reported a highly enantioselective, chelation-controlled Heck arylation of prolinol vinyl ether by Pd(OAc)₂ catalysis in a 1:10 H₂O/DMF mixture under air, which provided moderate to good yields (45–78%) and excellent ee's (90–98%) for the isolated cyclopentanones [221]. A successful MW-assisted regioselective diarylation of the chelating *N,N*-dimethyl(2-ethenoxy)ethanamine was described by Larhed and co-workers, using Herrmann's catalyst; both electron-rich and electron-poor aryl substrates demonstrated good yields after 10–120 min at 160–200 °C (Scheme 29) [222].

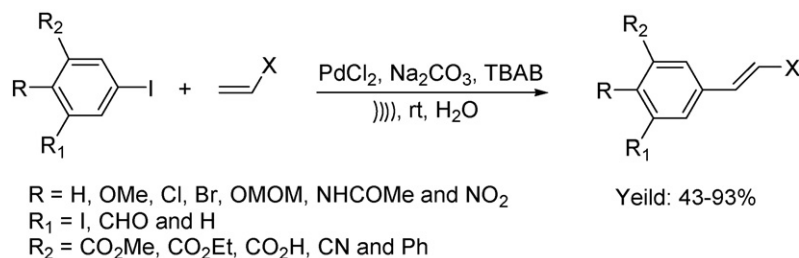
A facile, cationic surfactant-aided, ligand-free Heck arylation in water was recently reported [223]. Pd(OAc)₂ or PdCl₂ catalyzed coupling reactions of electron-rich and -deficient aromatic bromides or iodides with electron-deficient olefins such as acrylate, acrylonitrile or styrene proceeded in water in the presence of the cationic surfactant CTAB at 80–130 °C to give

80–95% yields. Under ultrasonic irradiation, the ligand-free catalysis can be carried out in water at ambient temperature, affording linear products in moderate to good yields (Scheme 30) [224]. Increasing the reaction temperature to 60–90 °C, the corresponding polycoupling products were obtained. *In situ* generated Pd nanoparticles were considered to contribute to the catalysis efficiency [223,224].

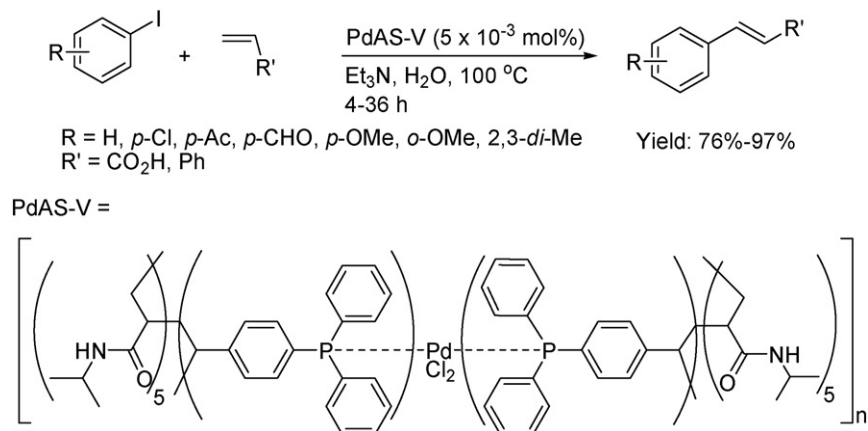
Phosphine ligands have also found good use. A number of reports have been published recently in this respect. For instance, Shaughnessy and co-worker reported that tri(4,6-dimethyl-3-sulfonatophenyl)phosphine (TXPTS) [225] or 2-(di-*tert*-butylphosphino)ethyltrimethylammonium chloride (*t*-Bu-Amphos) [226] was superior to the commonly-used water-soluble TPPTS in Pd-catalyzed aqueous-phase Heck couplings of aryl bromides under relatively mild conditions (80 °C). Sinou and co-worker demonstrated the asymmetric arylation of 2,3-dihydrofuran with aryl triflates in water in the presence of (*R*)-BINAP and a surfactant C₁₆H₃₃N⁺Me₂(CH₂)₃SO₃[−] (HDAPS), which proceeded with high regioselectivities, and moderate conversions and ee's under very mild conditions (45 °C) [227].

For easy separation and recovery of catalyst, supported catalysts with either a phosphine-free [228–231] or a phosphine ligand [232] have been studied in aqueous-phase couplings. For example, the coupling of aryl iodides with acrylic acid led to the corresponding cinnamic acids in high yields in water under mild conditions; the catalyst was assembled from (NH₄)₂PdCl₄ and an amphiphilic polymer poly[(*N*-isopropylacrylamide)₅-*co*-(4-diphenylphosphinostyrene)]. As shown in Scheme 31, the catalyst was highly efficient, with loading as low as 5.0 × 10^{−3} mol% [232]. The catalyst was also effective in toluene, giving an average yield of 94% in a total of five consecutive runs with a TON of 1,150,000 and a TOF of 12,000 h^{−1} in the case of the coupling of iodobenzene with methyl acrylate under the same conditions.

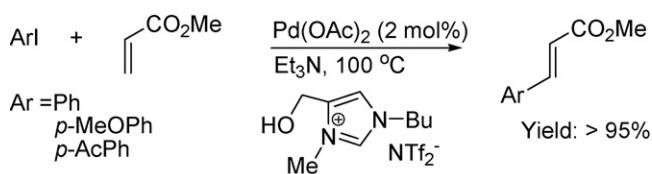
A report by Perosa et al. showed a 10-fold acceleration in Pd/C catalyzed arylation of aryl iodides with electron-deficient olefins and styrene in an isooctane–water system by using a catalytic amount of the phase-transfer catalyst Aliquat 336 (A336) [229]. For aryl bromides, the reaction became sluggish, however. More recently, Suzuki and co-workers reported that Pd(OAc)₂, immobilized on a reversed-phase amorphous silica gel with the aid of an IL [bmim]PF₆, was highly efficient for Heck coupling of iodobenzene with cyclohexyl acrylate in neat water without using a ligand, with TON and TOF reaching 1,600,000 and 71,000 h^{−1}, respectively [231].



Scheme 30.



Scheme 31.



Scheme 32.

The Heck reaction has been increasingly explored in ILs in recent years, with ligand-free, phosphine-free, and phosphine-enabled catalysis all being seen. Kabalka et al. reported that the Heck coupling, catalyzed by Pd(OAc)₂ alone, of arylidiazonium tetrafluoroborate salts with electron-deficient olefins such as methyl acrylate and methyl acrylonitrile proceeded smoothly in [bmim]PF₆, to give normal coupling products in moderate to good yields (68%–82%) under mild conditions (rt or 50 °C for 2–4 h) with efficient catalyst recycle without losing activity. However, for electron-rich olefins such as butyl vinyl ether or vinyl acetate, no coupling was observed, and for styrenes, dimerization products were observed [233].

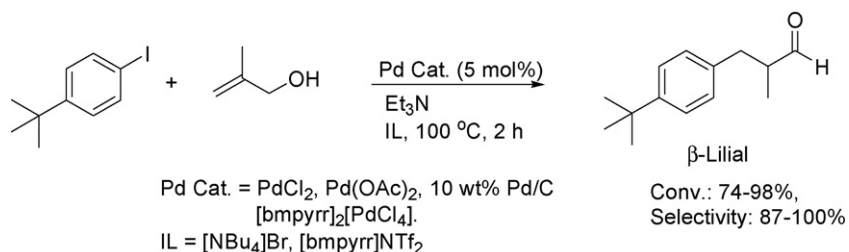
The simple Pd(OAc)₂ was also applied to the Heck reaction of aryl iodides in a polar, fructose-derived IL, 2-hydroxy-1-methyl-3-butyl imidazolium triflimide [234]. As shown in Scheme 32, the reaction was complete within 1 h at 100 °C to give >95% yields. By simple extraction of the product using cyclohexane, the catalyst could be recovered and recycled several times with no detectable loss in activity. However, in the case of

aryl bromides, no reaction occurred under the same conditions. Furthermore, kinetic studies showed this IL to be less effective than the imidazolium-based one, such as [bmim]NTf₂ and [bmim]BF₄. It was further shown that a catalytic amount of halides has an interesting accelerating effect on the reaction [235].

On the other hand, the phosphonium salt IL, trihexyl(tetradecyl)phosphonium chloride (THP-Cl), was shown to be ideal for the Heck arylation of aryl iodides and bromides with acrylates and styrene with Pd(OAc)₂, especially when NaOAc–H₂O was used as base [236]. High yields (81–90%) with complete stereo- and regiocontrol were obtained under relatively mild conditions (50–100 °C, 2–4 h) with successful catalyst recovery and recycle. PdCl₂ catalyzed Heck reactions in ILs were also reported [237,238]. For instance, substituted benzofurans were obtained in moderate to good yields by a PdCl₂ catalyzed intramolecular coupling in [bmim]BF₄, and the catalyst in the IL phase could be recycled [237].

β-Lilial, an important intermediate for the production of fenpropimorph (Corbel®) (a biodegradable fungicide) and fragrance, could be efficiently synthesized by a one-step Heck coupling with ligand-free Pd catalysis in ILs, as shown in Scheme 33 ([bmpyrr] = 1-butyl-1-methylpyrrolidinium) [239].

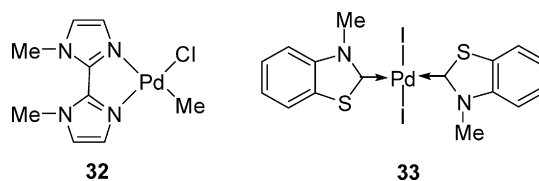
ILs were demonstrated to be the medium of choice for *in situ* investigation of colloidal Pd catalysts [240]. Caló et al. reported that Pd nanoparticles catalyzed the regio- and stereoselective arylation of 1,1-disubstituted alkenes in the IL TBAB using tetra-*n*-butylammonium acetate (TBAA) as base [241].



Scheme 33.

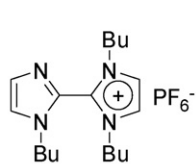
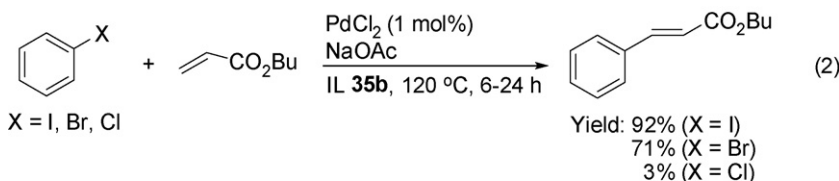
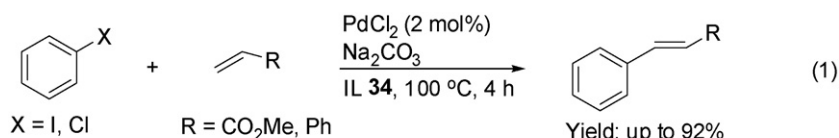
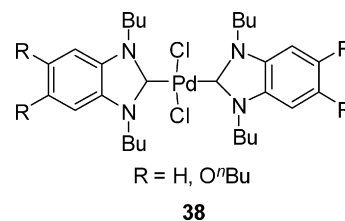
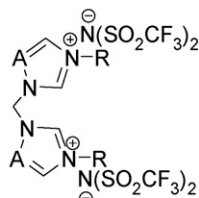
The efficacy of this system was attributed to metal nanoparticles being stabilized by TBAB and a fast neutralization of Pd-H by TBAA. Chitosan and poly[β -(1–4)-2-deoxy-D-glucan] supported Pd nanocolloids were applied to the Heck reaction of aryl halides including activated chlorides in ILs by the same group [242]. The reaction was fast in TBAB in the presence of TBAA as a base at 100–130 °C to give 85–98% yields of the products in 15 min. Recently, the group reported that Cu nanoparticles, derived from the reaction of iodobenzene with copper bronze, were an efficient catalyst for the Heck arylation of aryl iodides and activated bromides in TBAB in the presence of TBAA [243]. However, the heterogeneous catalysis was somewhat slower, particular in the Heck arylation of aryl chlorides; but the reaction time could be made considerably shorter by MW heating [244].

Pd complexes bearing phosphine-free ligands such as carbenes have good solubility in ILs and have often been used as catalyst in ILs. For example, Alper described a Pd(II)-bisimidazole complex **32**, which was efficient for Heck reactions in [bmim]PF₆ [245]. The reaction of a spectrum of aryl iodides, bearing electron-withdrawing or -donating groups, with either electron-deficient or -rich olefins proceeded readily in most cases, furnishing high product yields at a 2 mol% of catalyst loading and 120 °C. A sequential double-Heck reaction with different iodoarenes could also be effected. Moreover, the IL-catalyst phase could be recycled five times without any loss in activity. The monodentate carbene Pd(II) complex **33** displayed good performance in the stereospecific coupling of cinnamates with aryl halides in TBAB [246]. The reaction was performed with 1.5 mol% of catalyst in the presence of TBAA at 130 °C, affording 90–95% yields of β -aryl-substituted cinnamic esters within 4–5.5 h.

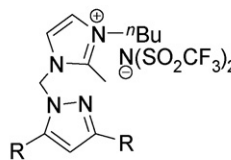


Shreeve and co-worker recently synthesized a series of functionalized ILs, **34–37**, Scheme 34 [247–249]. Being coordinating and/or potential carbene precursors, these solvents were evaluated in PdCl₂ catalyzed Heck coupling of aromatic halides with acrylates. IL **34** was shown to be a good solvent and ligand for the coupling of both iodo- and chlorobenzene with methyl acrylate and styrene, affording a high yield of product at 100 °C in air for 4 h, with a good IL-catalyst recyclability (Eq. (1)) [247], while the others were good for iodobenzene and poor for chlorobenzene (Eq. (2)) (Scheme 34) [248]. The key catalyst species in some of the reactions were considered to be Pd-carbene complexes generated *in situ* from the solvents.

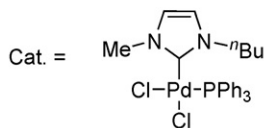
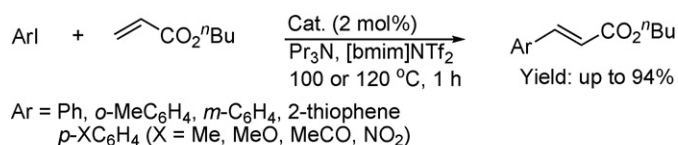
Heck reaction of aryl bromides and activated aryl chlorides was reported to be efficiently catalyzed by the (benzimidazolylidene)-palladium catalyst **38**, which was generated *in situ* from the corresponding benzimidazolium and PdCl₂ in TBAB. The reaction provided moderate to good yields of product, with controllable mono- and diarylation of terminal olefins [250].

**34**

35 a-e: A = C
36 a-e: A = N
 R = CH₃ (**a**), C₄H₉ (**b**), C₆H₁₃ (**c**),
 (CH₂)₃CF₃ (**d**) and (CH₂)₂C₄H₉ (**e**)



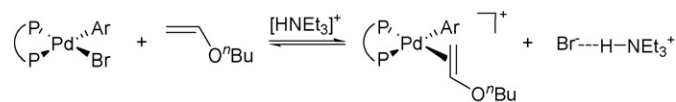
37a: R = H
37b: R = CH₃



Scheme 35.

Phosphines generally have good solubility in ILs and are commonly used as ligand. Ryu and co-workers used a phosphine and *N*-heterocyclic carbene Pd(II) complex as a source of palladium to provide stable homogeneous solution in a low-viscosity IL [bmim]NTf₂ (Scheme 35) [251,252]. In the arylation of *n*-butyl acrylate with a variety of aryl iodides in this solution, up to 94% yield was provided at 100–120 °C after 1 h [251]. After separation of the product by a triphasic workup (hexane-water-IL), the catalyst-containing IL layer could be further used up to six runs without any loss in activity. This low-viscosity IL system benefited a continuous microflow method aimed for catalyst recycling [252]. A multi 10-g scale preparation of *n*-butyl cinnamate (10 g/h), difficult to accomplish by common synthetic methods in a batch system, was achieved from the coupling of iodobenzene with *n*-butyl acrylate by applying this microflow system.

In a series of papers [253–260], the group of Xiao showed that electron-rich olefins, including vinyl ethers, allyltrimethylsilane, vinyl enamides and allylic alcohols, can be arylated highly regioselectively with (hetero)aryl iodides or bromides with Pd-DPPP (DPPP = 1,3-bis(diphenylphosphino)propane) catalysis in IL, such as [bmim]BF₄ [253–256,258,259], [bmim]PF₆ [260] or an IL–organic solvent cocktail [257], without recourse to any halide scavengers or triflate substrates. It is believed that the ionic medium promotes the formation of a cationic palladium species that is key to the formation of the α arylated product. As shown in Scheme 36, vinyl ethers could be readily arylated by electron-rich or electron-poor aryl bromides and iodides to give exclusively branched products; high yields of methyl ketones were obtained following hydrolysis by acid [255]. Good yields with exclusive α -regioselectivities were also obtained for arylation of allyltrimethylsilane (82–93%) in neat [bmim]BF₄ or vinyl



Scheme 37.

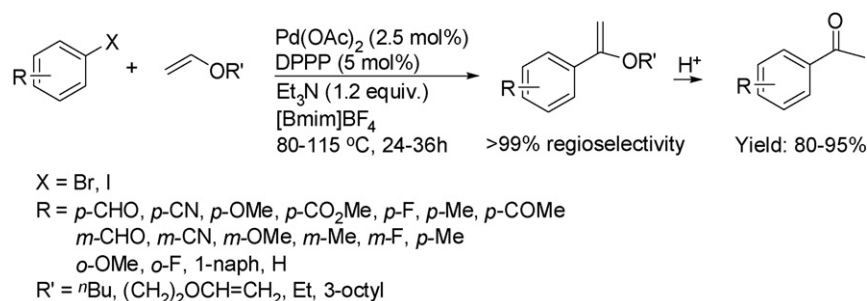
enamides (71–85%) by aryl bromides in a [bmim]BF₄–DMSO (1:1, v/v) mixture under similar conditions [255].

Interestingly, ammonium salt-based hydrogen bond donors such as [Et₃NH]BF₄ and [H₂N^{*i*}Pr₂]BF₄ could dramatically accelerate the reaction occurring not only in ILs [255,258] but also in common solvents like DMF [258] and DMSO [261]. For example, butyl vinyl ether was arylated by bromoacetophenone to give a 78% conversion over 1 h by Pd-DPPP (2.5 mol%) in the presence of [Et₃NH]BF₄, while only 2% conversion was obtained without the ammonium salt under otherwise identical reaction conditions [258]. A further example is seen in the same coupling reaction catalyzed by Pd-*m*BDPP (2 mol%) (*m*BDPP = *meso*-2,4-bis(diphenylphosphino)pentane), which was completed in DMSO in 24 h when [Et₃NH]BF₄ was added; but in the absence of the salt additive, it took 36 h even at a higher catalyst loading (4 mol%) [261]. It was proposed that the formation of hydrogen bonding between the ammonium salt [H_{*n*}NR_{4–*n*}]BF₄ (*n* = 1, 2) and the dissociated Br[–] from the L₂PdBr(Ar) complex, resulting from the oxidative-addition of Ar–Br, accounts for the accelerating effect on the reaction rate as shown in Scheme 37.

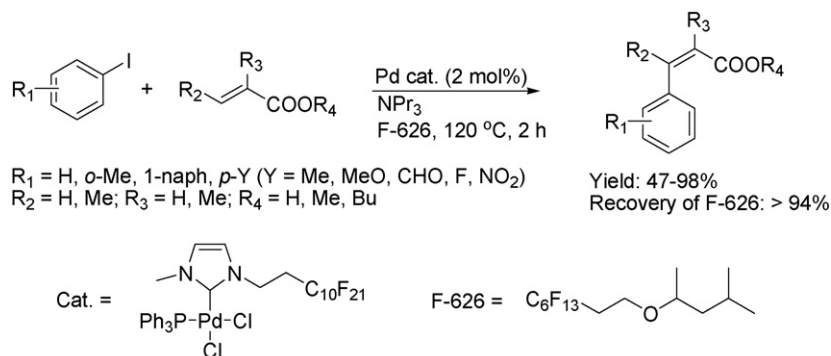
The ionic medium could also promote the regioselective arylation of functionalized haloarylphosphine oxides [254]. Thus, bromophenylphosphine oxides were olefinated by *n*-butyl vinyl ether under Pd-DPPP catalysis at 125 °C in [bmim]BF₄, affording 51–79% acetylated phosphine oxides after acidification; no β -arylated products were detected.

Heck reaction has also been explored in scCO₂ and fluorous solvents, although less successful than those in aqueous phase and ILs. This is at least partly due to the Heck reaction usually requiring the use of dipolar solvents. Heck reaction in scCO₂ could be effected homogeneously by using scCO₂-soluble fluorinated catalysts [262,263], or biphasically as demonstrated by Arai and co-workers, by using a water-soluble ligand, such as TPPTS, and water as a co-solvent [264]. Multiphase catalysis involving scCO₂ offers a further possibility [265].

Fluorous catalysts such as the palladacycles **39** and **40** [266], the SCS pincer complex **41** [267] and the ligands F-dppp **42** [268] and F-BINAPs **43** and **44** [269,270] have recently been

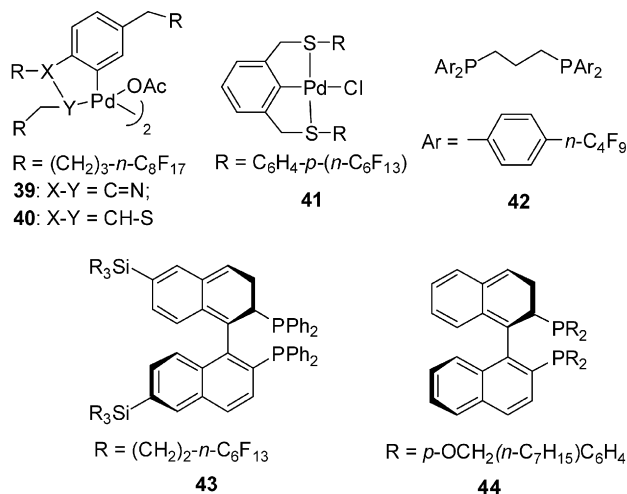


Scheme 36.



Scheme 38.

studied as ligands/catalysts for Heck reaction, either in organic or fluorosolvents. For example, complex **41** was shown to be efficient for the Heck arylation of methyl acrylate and styrene by aryl bromides, iodides and triflates in DMA under thermal or microwave heating at 140 °C, providing high yields for the corresponding coupling products. The catalyst was reusable via fluorosolvent extraction using a fluorosolvent reversed-phase silica gel [267]. The F-BINAP **43** in combination with Pd(OAc)₂ was employed as a catalyst for the asymmetric Heck reaction between 2,3-dihydrofuran and 4-chlorophenyl triflate at 40 °C in a biphasic system of FC-72 plus benzotrifluoride or benzene; up to 93% ee was obtained for the desired product 2-(4-chlorophenyl)-2,3-dihydrofuran [269].



Ryu and co-workers demonstrated the Mizoroki–Heck arylation of α,β -unsaturated carboxylic acids and esters in a fluorosolvent ether F-626, using a fluorosolvent Pd-carbene complex as catalyst [271]. As shown in Scheme 38, the reaction proceeded successfully to give moderate to high yields of the coupling products, with almost complete recovery of the fluorosolvent-containing catalyst by simple filtration. The recovered solvent-catalyst mixture could be further used for six runs by employing fresh reactants, without loss of activity.

2.3.2. Suzuki coupling

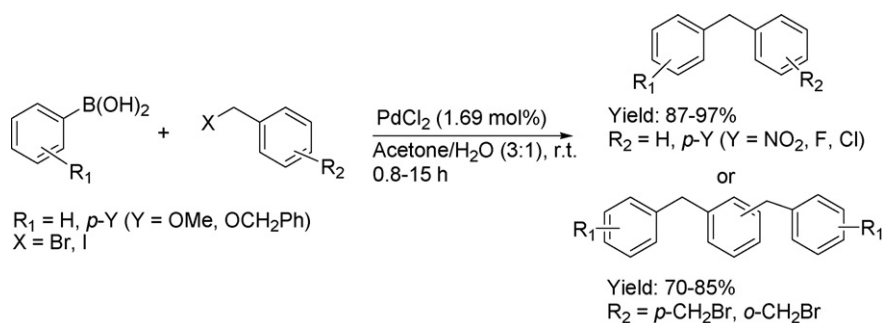
The Suzuki–Miyaura cross-coupling of aryl halides with aryl boronic acids is one of the most powerful methods for the con-

struction of biaryls, which are valuable compounds used in synthesis of pharmaceuticals, agrochemicals and new materials. Boronic compounds are usually quite stable and insensitive to air and water, and so can be easily handled in a variety of solvents apart from those commonly used in cross-coupling reactions.

Amongst the alternative reaction media, water has proved to be viable for the Suzuki reactions. From 2003 onwards, a great number of reports in this area have appeared in the literature, and some latest reviews are found in papers by Leadbeater [272] and Xu and co-workers [273], the latter focusing on asymmetric Suzuki reactions in aqueous–organic media.

Using neat water or a water–organic mixture as solvent, it is feasible to conduct the Suzuki reaction by simple Pd(OAc)₂ or even Pd/C in combination with a surfactant without using a ligand. For example, a report by Arcadi et al. [274] showed that in the presence of CTAB and K₂CO₃, the coupling of iodoanisole, aryl bromides and activated aryl chlorides with aryl boronic acids catalyzed by Pd/C (2.5 mol%) occurred at room temperature (for the bromides and iodides) or 100 °C (for aryl chlorides) in air, with high yields (>85%) after 24 h, easy catalyst/product separation and good catalyst recyclability. Pd(OAc)₂ was shown to be effective in the cross-coupling of less reactive aryl chlorides at 100 °C [274]. More recently, Sengupta and co-workers [223] reported that PhB(OH)₂ smoothly coupled with 4-iodoanisole and 4-acetylbenzyl bromide in water in the presence of CTAB and 1% Pd(OAc)₂ at 100 °C to give 80–90% of biaryls over 1–3 h reaction time. Pd/C catalyzed couplings between aryl bromides and sodium tetraarylborates in water were also reported, and excellent product yields were achieved without using any surfactants, particularly when using sodium hydroxide or carbonate as base [275].

PdX₂ (X = OAc or Cl) catalyzed Suzuki coupling could also be performed in water/organic mixtures. As shown in Scheme 39, diarylmethanes were produced in high yields by the couplings of benzylic halides with aryl boronic acids using PdCl₂ as catalyst in an acetone/water (3:1) mixture under mild conditions [276]. A similar catalytic performance was recently reported by Zhang and co-workers, who demonstrated that the use of a suitable amount of a co-solvent was key for this successful catalytic system [277]. Furthermore, benzoyl chlorides could be coupled with tetraphenylborates (Ph₄BNa) in H₂O or aqueous acetone by using PdX₂ to give non-symmetric biaryl ketones [278].



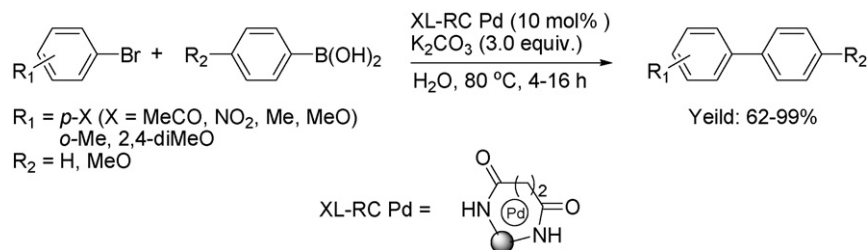
Scheme 39.

Pd, encapsulated into a thiol-functionalized mesoporous silicate SBA-15-SH, was demonstrated to act as an efficient catalyst for Suzuki reactions in either water or a DMF/H₂O (20/1) mixture [279]. The reaction of a spectrum of (hetero)aryl bromides and activated aryl chloride with phenylboronic acid proceeded smoothly (1 mol% Pd, 80–90 °C for aryl bromides and 2 mol% Pd, 100 °C for aryl chloride) to give 82–98% yields without leaching of Pd (<3 ppb). A test on the heterogeneity showed that the catalysis occurred in a heterogeneous process. Pd(0) loaded on NaY zeolite, prepared by the reduction of Pd(II)-exchanged NaY, was reported to be highly active for the Suzuki coupling of aryl bromides and arylboronic acids in DMF/H₂O (1:1) using Na₂CO₃ as a base at room temperature [280]. [Pd(NH₃)₄]²⁺ immobilized on Sepiolite, a natural clay, has been applied to the Suzuki reaction of 4-bromophenol with phenylboronic acid or sodium tetraphenylborate in water in air at room temperature, resulting in a high yield than unsupported Pd(II) salts. The formation of small Pd clusters (2–7 nm) during the catalytic process was confirmed [281]. Bradley and co-workers recently reported a cross-linked resin-captured palladium catalyst, which was prepared by diffusing Pd(OAc)₂ into swollen resins followed by cross-linking of amino groups on the resin (Scheme 40) [282]. The catalyst was shown to be efficient for the Suzuki coupling of both activated and deactivated aryl bromides with aryl boronic acids in water to give good yields of biaryl products (62–99%) with good catalyst recyclability; but it exhibited poor activity for aryl chlorides. The applicability of the catalyst was demonstrated in the synthesis of a sulfophthalein dye without any palladium contamination, which can cause serious problems in the optical properties of the product.

In earlier studies, Leadbeater et al. reported that using either conventional or MW heating, Suzuki coupling in water could be promoted by palladium with loading down to 10⁻⁸ mol% (*i.e.* 50 ppb), which could be supplied by the impurity in the

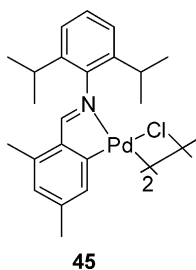
Na₂CO₃ base used [283–286]. This was originally thought to be a transition metal-free process [283,284,287]. Thus, aided by microwave heating, the Suzuki coupling of aryl halides (iodides, bromides and chlorides) with a number of potassium organotrifluoroborates proceeded successfully with 2.5 ppm palladium in water in the presence of Na₂CO₃ as base and TBAB as phase transfer reagent, providing moderate to very good yields (up to 96%) of the products in 5 min reaction time [286].

Palladium complexes without phosphine ligands provide another avenue for the Suzuki cross-coupling in aqueous media. As abovementioned in the Heck reaction, the complex (di-2-pyridyl)methylamine-palladium **30** proved also to be efficient for Suzuki coupling in neat water or aqueous media, using K₂CO₃ or KOH as a base in the presence of TBAB as an additive [214,288]. A range of aryl bromides and chlorides, and allyl chlorides, acetates and carbonates, could be successfully coupled with aryl- or alkyl-boronic acids or trimethylboroxine in water, or in DMF/H₂O (95/5) and MeOH/H₂O aqueous phases, to give moderate to excellent yields. For instance, with a 0.1–1% palladium loading, the coupling between aryl or benzyl chlorides and aryl boronic acids, in H₂O using K₂CO₃ as a base at 100 °C or in an acetone/H₂O (3/2) mixture at room temperature using KOH as a base, provided 51–97% isolated yields of the products; the coupling of allyl chlorides, acetates and carbonates with aryl-boronic acids in water using 0.05–1% catalyst at 100 °C gave rise to 83–97% isolated yields. Trimethylboroxine and alkyl-boronic acids were coupled with aryl bromides or chlorides in water at reflux to yield methyl- and butyl-arenes; however, up to 5 mol% Pd loading was needed [288]. The reaction in water took place faster and more efficiently, with TOF (h⁻¹) up to 125,000 observed in the case of coupling of 4-bromophenol with phenyl boronic acid [288]. It is noted that the reaction of aryl chlorides was run in the presence of TBAB acting as an additive. The reactions could be accomplished in a shorter time by microwave

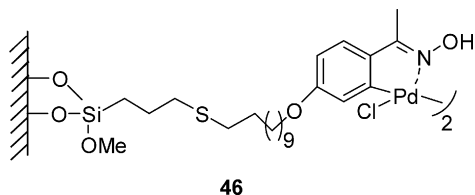


Scheme 40.

irradiation. An analogue to catalyst **31**, the cyclopalladated complex **45**, was reported to be an excellent catalyst for the Suzuki couplings of aryl bromides and activated aryl chlorides in water in air; TBAB was again necessary in the case of aryl chlorides [289].



Supported phosphine-free Pd-complexes have also been shown to be active for the Suzuki reaction in aqueous phases. For instance, the polymer-supported di(2-pyridyl)methylamine-palladium complex shown in Scheme 27 was not only active for the Heck reaction but also highly active for the Suzuki coupling in neat water, with TON up to 10^5 [216]. The oxime-carbapalladacycle complex in Scheme 28 was covalently anchored onto silica to give the catalyst **46**, which was reported to be very active for the Suzuki reaction of 4-chloroacetophenone and phenylboronic acid in water and to be reusable without any decrease in activity [290,291].



Polymer-supported palladium complexes containing *N*-heterocyclic carbene (NHC) ligands have also been shown to be active for Suzuki reactions in aqueous media [292,293]. For example, as shown in Scheme 41, the polymer-supported Pd-NHC complex [polymer = poly(1-methylimidazoliummethyl styrene)-surface grafted-poly(styrene) resin] catalyzed the Suzuki coupling of aryl iodides or bromides with a range of aryl boronic acids in a DMF/H₂O (1:1) mixture under mild con-

ditions (50 °C in air, 1 mol% Pd loading), to afford high yields and offer up to 10 times catalyst recyclability [293].

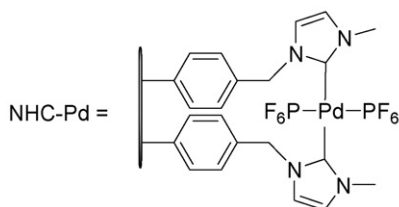
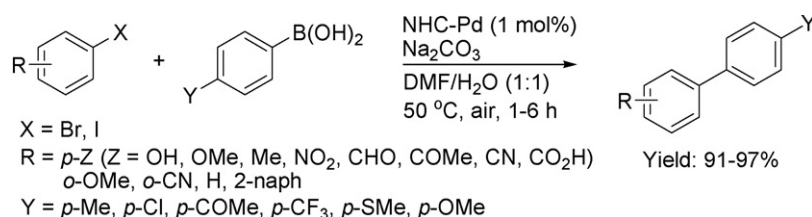
Pd(PPh₃)₄ is usually unstable, losing catalytic activity upon exposure to air. However, when supported on PEG-modified mesoporous silica, it displayed a high activity for the Suzuki coupling of aryl iodides and bromides with a set of aryl boronic acids in water under mild conditions (0.1 mol% of Pd, K₃PO₄, base, 50 °C and 10 h reaction time), affording excellent yields of the products (91–98%) with very good recyclability; the catalyst was still effective even after exposure to air for 6 weeks [294]. However, it is likely that the catalyst has adopted a new form rather than Pd(PPh₃)₄.

In addition to palladium, [RuCl₂(*p*-cymene)]₂ immobilized on Al₂O₃ was shown to efficiently catalyze Suzuki coupling of a wide range of aryl iodides with both boronic acids and boronate esters with 1 mol% catalyst loading in DME/H₂O (1:1) (DME = 1,2-dimethoxyethane) at 60–90 °C, furnishing >90% yields with high product purity in most cases. The reaction could be scaled up to a few grams without any practical problems [295].

Water-soluble phosphine palladium complexes can be used as catalysts in Suzuki reactions in water or aqueous media. For example, Pd/TXPTS [225] and Pd/*t*-Bu-Amphos [226] were shown to be active catalyst precursors for Suzuki coupling of aryl bromides in water or a water/organic biphasic mixture under mild conditions, and even at room temperature in the case of the latter. Both catalysts were further shown to be superior to Pd/TPPTS or Pd/TMAPTS (TMAPTS = tri(4-methoxy-6-methyl-3-sulfonatophenyl)-phosphine trisodium salt).

A drawback of Suzuki couplings in water is the phase-transfer limitations arising from water-insoluble substrates. To circumvent this problem, the use of surfactants [214,274,276,288,289] or mass transfer promoters [296] has been explored. Cyclodextrins and calixarenes were reported to be useful inverse phase-transfer promoters for Suzuki couplings in aqueous medium; the latter was much better than the former in inducing rate enhancement, but troublesome in separation of the aqueous layer from the organic phase [295].

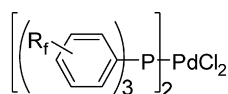
The self-assembled Pd-phosphine catalyst PdAS-V (Scheme 31) was reported to efficiently catalyze a heterogeneous Suzuki reaction of aryl and alkenyl halides (iodides



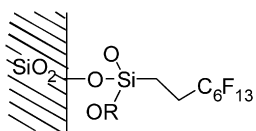
Scheme 41.

or bromides) and benzylic chlorides with arylboronic and alkenylboronic acids in water or in organic solvents at 100 °C, affording high yields with easy workup and catalyst recycling; up to 1,250,000 TON was observed in the case of the coupling of iodobenzene with phenylboronic acid [297]. Self-assembled amphiphilic rod–coil molecules, comprised of hexaphenylene rod segments linked to poly(ethylene oxide) coil units, have been reported to be a supermolecular reactor for Suzuki coupling of a range of aryl halides including aryl chlorides with phenyl boronic acid in water at room temperature, affording moderate to high yields [298].

Perfluoro-tagged Pd catalysts **47a–e**, supported on fluorous reversed-phase silica gel **48**, were reported by Bannwarth and co-workers to be useful for Suzuki reaction in water [299]. The Pd-loading was as low as 0.001 mol%, with TON reaching 217,000 at 80 °C. The catalytic process was suggested to be homogeneous, despite the pronounced hydrophobicity of the catalysts. A detailed kinetic study on the use of this kind of catalyst in Suzuki reactions in both organic solvent and water was presented by the same group recently [300].

**47**

R_f = H (**a**), *p*-C₈F₁₇(CH₂)₂ (**b**), *m*-C₈F₁₇(CH₂)₂ (**c**), *p*-C₈F₁₇ (**d**), *p*-C₇F₁₅CH₂O (**e**)

**48**

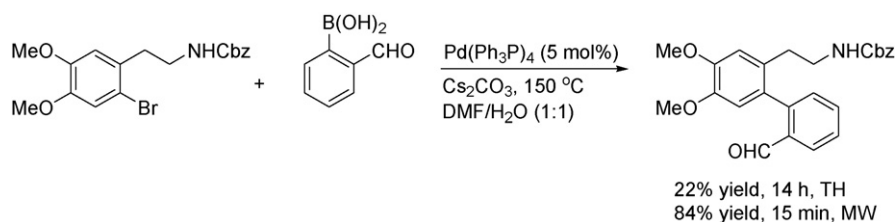
As abovementioned, MW heating has recently been shown to be an efficient method in promoting the Suzuki reaction either in neat water or in aqueous media [283–285,288,301,302]. For example, the reaction rate of the coupling between a phenethylamine and (2-formylphenyl)boronic acid in DMF/H₂O was dramatically increased by MW heating, compared to that by thermal heating (TH) under the same conditions; the product was obtained in 84% yield after 15 min in the former case, which compares much favourably with the 22% yield after 14 h under TH (Scheme 42). The product from the reaction is a useful intermediate for the total synthesis of aprotalanthamine analogues, an intriguing class of natural products endowed with interesting biological activity [301].

A highly efficient Suzuki coupling was reported of aryl perfluorooctylsulfonates with boronic acids under MW heating. The reactions were performed in a toluene/acetone/water (4:4:1) mixture using 10 mol% PdCl₂(dppf) [dppf = 1,1'-bis(diphenylphosphino)ferrocene] at 100–130 °C for 10 min, giving 75–95% yields of the products; the product separation and purification was effected over a fluorous silica gel [302]. The catalyst was also shown to be highly active for the Suzuki reaction of aryl bromides in water alone, providing biaryls in excellent yields (81–99%) with high TONs (up to 870,000 in the case of 1-bromo-4-nitrobenzene reacting with phenylboronic acid) [303]. In the presence of a small amount of PEG-2000, the catalyst could be recycled retaining consistency in activity.

High-intensity ultrasonic irradiation offers another method to promote the Suzuki reaction in aqueous phase, specifically in the case of heterogeneous catalysis [304,305]. In addition, microreactor or capillary-microreactor was reported to offer a convenient and useful means to perform Suzuki reactions in aqueous media, due to its large surface area, highly efficient mixing and excellent mass and heat transfer properties [306,307].

Suzuki coupling has also been investigated in other alternative solvents, but to a lesser degree than in water. The reaction conducted in ILs offers several potential advantages over conventional organic solvents, such as increased catalyst life and reactivity, and decreased homocouplings. Several types of ILs, such as imidazolium [251,308], phosphonium [309], alkylammonium [310] and pyridium salts [311], have been successfully demonstrated to be viable for Suzuki reactions.

In imidazolium-based ILs, Suzuki reactions of bromo- and iodo-arenes have been performed with both increased reactivity and catalyst stability. Both Pd(0) and Pd(II) compounds can be used as source of palladium, with soluble, ionic Pd(II) salts preferred [308,312]. Welton and co-workers [312] reported that N-donor stabilized palladium complexes made *in situ* from PdCl₂(CH₃CN)₂ and imidazoles were active catalyst precursors for the Suzuki coupling of aryl iodides and bromides with *p*-methylphenyl boronic acid in imidazolium ILs (1.2 mol% Pd, 110 °C, aqueous Na₂CO₃ as a base), and the catalyst was stable and recyclable. Four equivalents of imidazole, relative to palladium, were required to prevent catalyst decomposition, with 1-phenylimidazole and 1-methylbenzoimidazole providing the most active catalyst in [bmim]BF₄. Carbene complexes generated *in situ* were considered to be the active catalytic species, however. Similarly, the Pd-carbene complex reported by Ryu and co-workers [251] shown in Scheme 35, catalyzed the Suzuki coupling of (hetero)aryl bromides and iodides with phenyl boronic acid in a mixture of low viscosity IL and water

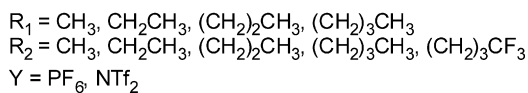
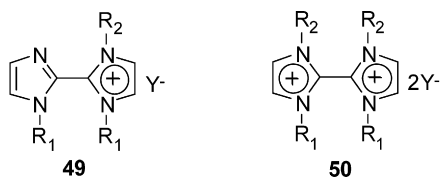


Scheme 42.

[bmim]NTf₂/H₂O (1:1), affording moderate to good yields of the products (2 mol% Pd, 100 °C, Na₂CO₃).

The synthesis of quinoline and isoquinoline heterocyclic compounds by Pd(PPh₃)₄-catalyzed Suzuki reaction of heterocyclic chlorides with naphthaleneboronic acids in [emim]BF₄ was recently described by Sun and co-worker [313]. The reaction proceeded smoothly at 110 °C in aqueous Na₂CO₃ to give in 10 min moderate to good yields after acidification. Only substrates in which the chlorine and nitrogen were in the same ring worked; the reaction did not occur for substrates with chlorine and nitrogen in different rings or without nitrogen. It was suggested that the nitrogen would favour the oxidative-addition step in the catalytic cycle.

Shreeve and co-workers synthesized mono- (**49**) or diquantaternized (**50**) 2,2'-biimidazolium-based ILs; (also see Scheme 34). One of those, 1,3,1'-tributyl-2,2'-biimidazolium hexafluorophosphate was employed as both solvent and ligand for the Pd-catalyzed Suzuki reaction of a variety of aryl bromides and phenyl boronic acid and was shown to be very efficient and recyclable [314]. The pyrazolyl-functionalized imidazolium ILs, represented by IL **37** in Scheme 34, was also a suitable solvent for the Suzuki reaction, in which activated aryl bromides coupled with phenyl boronic acid within 1 h to give high yields of the binary products under the conditions of 2% Pd-catalyst at 110 °C [249].



Task-specific ILs have been designed to aid catalysis and applied to the Suzuki coupling. Dyson and co-workers synthesized nitrile-functionalized *N*-butylnitrile pyridinium ILs [C₃CNpy]X (X = Cl⁻, BF₄⁻, PF₆⁻, NTf₂⁻) ([C₃CNpy] = *N*-butylnitrile pyridinium), which reacted with PdCl₂ to form the complex [C₃CNpy]₂[PdCl₄] or [PdCl₂(C₃CNpy)₂][anion]₂ (anion = BF₄⁻, PF₆⁻, NTf₂⁻) [311]. These Pd-complexes catalyzed the Suzuki coupling of iodobenzene with phenyl boronic acid in [C₃CNpy]NTf₂ or the non-functionalized IL [C₄py]NTf₂ ([C₄py] = *n*-butylpyridinium), displaying good catalytic activity in the first run; but the functionalized [C₃CNpy]NTf₂ was shown to be superior in the recycling runs, possibly due to the coordinating nitrile moiety that retarded Pd leaching (<5 ppm versus 28 ppm leaching in [C₄py]NTf₂).

Suzuki reaction was earlier explored by Gladysz and co-workers, using fluoros ligands in conjunction with palladium in fluoros media [315], and by Bannwarth and co-workers using fluorinated silica-supported palladium complexes containing fluoros ligands in conventional organic solvents [316]. However, catalyst decomposition was observed in subsequent runs in both cases. Gladysz and co-workers [266] also reported that the thermomorphic fluoros imine palladacycle **39** was

highly active for Suzuki reactions, this time in toluene, in which the catalyst exhibited little solubility at room temperature but a significant one at elevated temperature, thus enabling a homogeneous reaction at high temperature and easy catalyst/product separation upon cooling.

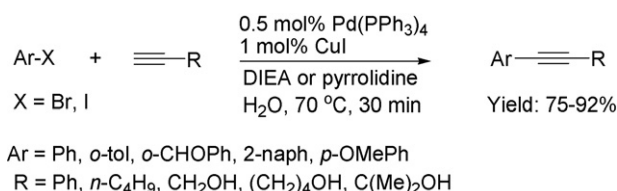
2.3.3. Stille coupling

Stille coupling, the reaction of organostannes with aryl/vinyl halides, is another useful C–C bond forming reaction. This reaction has been less investigated in the alternative solvents, however, partly due to the toxicity of organotin reagents and by-products. Dyson and co-workers [311] recently demonstrated a Stille reaction between iodobenzene and phenyltributylstannane catalyzed by the complexes aforementioned, [PdCl₂(C₃CNpy)₂]X₂ (X = PF₆⁻, BF₄⁻, or NTf₂⁻) or [C₃CNpy]₂[PdCl₄], in the ILs [C₃CNpy]NTf₂ and [C₄py]NTf₂. The reaction proceeded well in both ILs, but the former provided a better retention of the palladium than the latter, due to its coordinating nitrile group as in the case of the Suzuki reactions. Nanoparticles (*ca.* 5 nm) generated *in situ* were proved to be the active catalytic species. The Stille reaction of aryl iodides with tributylphenyltin in [bmim]NTf₂ could be effected by the Pd-carbene complex of Scheme 35, in the presence of triphenylarsine under copper-free conditions, as reported by Ryu et al. [251]. The reactions proceeded smoothly with 2 mol% Pd loading at 100 °C to afford moderate yields (75–82%) within 1.5–5 h, with the catalyst being recyclable. The effect of physicochemical properties of solvents on the transfer of vinyl and alkyl groups has recently been addressed in a study of the Stille coupling in various ILs [317].

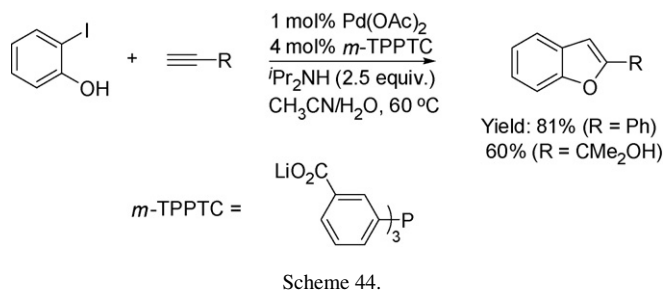
2.3.4. Sonogashira reaction

Sonogashira reaction, the alkylation of aryl or vinyl halides with terminal alkynes, is a powerful tool for the synthesis of substituted acetylenes. The reaction has been successfully performed in neat water or aqueous phase. For example, the alkylations of aryl halides with various alkynes have been achieved in neat water by Pd(PPh₃)₄ without any additive or phase transfer catalyst. As shown in Scheme 43, the reaction was remarkably fast using 0.5 mol% catalyst at 70 °C, affording high yields of the aryl alkyne products [318].

Aqueous-phase Sonogashira couplings can be aided with water-soluble phosphines [319,226]. For instance, Pd(OAc)₂ (1 mol%), in conjunction with a carboxylated phosphine *m*-TPPTC, catalyzed the copper-free cross-coupling of (hetero)aryl bromides and iodides including *ortho*-functionalized aryl iodides in a CH₃CN/H₂O mixture at 60–70 °C, leading to the alkynes in moderate to high yields [319]. Furthermore,



Scheme 43.



as shown in Scheme 44, 2-hydroxy-iodobenzene was coupled with terminal alkynes by the same catalyst to afford the cyclized product benzofurans in good yields.

The phosphine-free palladium complex **30** has been demonstrated to be active and efficient for the copper-free Sonogashira reaction of aryl iodides and bromides with terminal alkynes in water at reflux or even at room temperature under air in the presence of pyrrolidine as base and TBAB as additive, with TONs up to 7×10^4 and TOFs (h^{-1}) up to 6666 being obtained [214,320]. An example is seen in the coupling between (*E*)- β -bromostyrene and oct-1-yne by 1 mol% Pd at room temperature in water, affording the product enyne stereospecifically in 70% yield [320].

PdCl_2 alone without added ligand has also been employed as catalyst for Sonogashira reactions in water [320,321]. For instance, Liang et al. [321] reported a mild protocol for the copper-free alkylation of aryl iodides with a variety of terminal alkenes in water under aerobic conditions at 50 °C or room temperature, using PdCl_2 (1 mol%) as catalyst in the presence of pyrrolidine as base; good to excellent yields (65–97%) of the products were obtained. The same authors also described the synthesis of alkynyl ketones via $\text{PdCl}_2/\text{PPh}_3$ catalyzed, copper-free carboxylative Sonogashira coupling of aryl iodides with terminal alkenes; the reaction was carried out in water at room temperature under a balloon pressure of CO with Et_3N as base. The method was applied to the synthesis of flavones, furnishing moderate to high yields (35–95%) [322].

Palladium on carbon was reported to be active catalyst for the Sonogashira reaction in water or aqueous phases, in the presence of PPh_3 as ligand and CuI as co-catalyst [323–325]. NaY zeolite-entrapped simple salt, $[\text{Pd}(\text{NH}_3)_4]^{2+}$ (1 mol%), was also shown to be efficient, stable and recyclable for alkylation of aryl iodides and activated aryl bromides in $\text{H}_2\text{O}/\text{DMF}$ mixture at 80 °C [326]. MW-assisted, transition metal-free alkylation

reactions in water have been reported, but showing a limited scope [327,328].

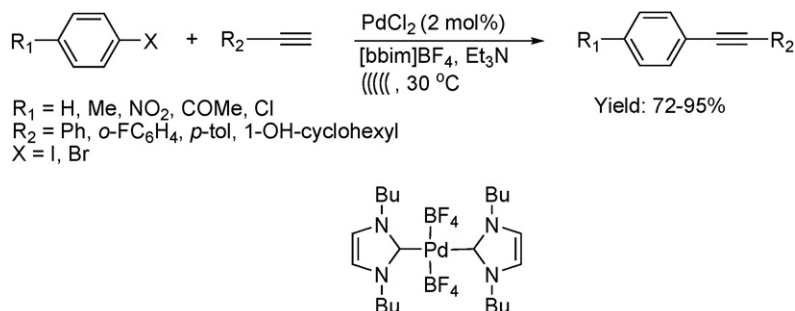
Sonogashira reaction has also been demonstrated in ILs. A recent example is provided by Alper and Park [329], who reported that the complex (bisimidazole) PdClMe (**32**) was an efficient and recyclable catalyst for the alkylation of aryl iodides with terminal alkynes in the absence of copper salts in $[\text{bmim}]\text{PF}_6$. More recently, Srinivasan and co-workers described copper- and ligand-free Sonogashira reactions that took place at ambient temperature under ultrasound irradiation in a series of imidazolium-based ILs, e.g. $[\text{bbim}]\text{BF}_4$ ($[\text{bbim}]$ = dibutylimidazolium) [330]. As shown in Scheme 45, the reaction proceeded in $[\text{bbim}]\text{BF}_4$ to give good yields for the desired products. The catalyst could be recycled five times with the same activity. The active catalytic species, confirmed by TEM, were believed to be palladium nanoparticles derived from the Pd-carbene complex shown. It is noteworthy that no reaction occurred at all without the ultrasonic irradiation even after 6 h reaction time.

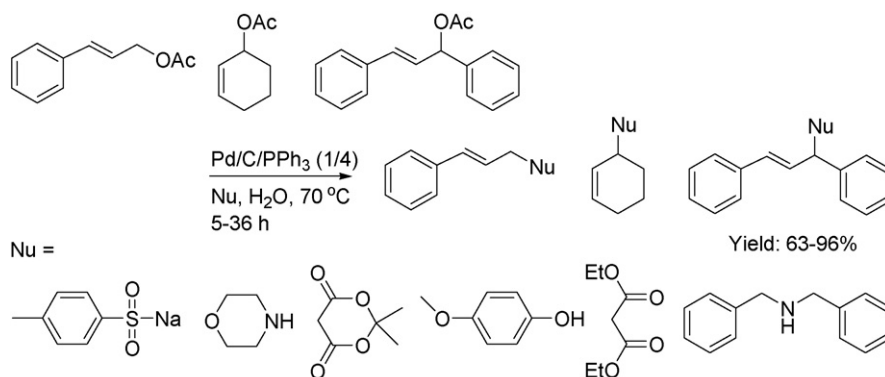
2.3.5. Allylic substitution

Pd-catalyzed allylic substitution, or the Tsuji–Trost reaction, is one of the established, important tools for the creation of a new carbon–carbon and carbon–heteroatom bonds. In general, the method involves the use of allylic acetates, carbonates, halides and phosphates *etc.*, instead of allylic alcohols as the hydroxy is not a good leaving group. The reaction has been successfully demonstrated in the alternative media in recent years.

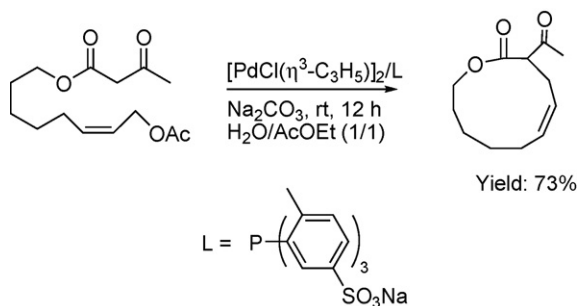
Water is a suitable solvent for the Tsuji–Trost reaction. In a recent report, Sinou et al. [331] demonstrated that the palladium-catalyzed asymmetric alkylation of 1,3-diphenyl-3-acetoxyprop-1-ene with dimethylmalonate can be readily performed in water in the presence of a surfactant and a base. It was shown that both the efficiency and the enantioselectivity of the reaction depended on the nature and concentration of the surfactant, with cationic ones being the best. Neutral or zwitterionic surfactants were poorer, and no reaction occurred with those that were anionic. Using BINAP as a ligand, up to 91% ee was obtained in the presence of a cationic surfactant and K_2CO_3 as base at room temperature.

In the presence of PPh_3 , Pd/C catalyzed the substitution of allylic acetates with a variety of nitrogen, sulfur and oxygen nucleophiles in water at 70 °C; moderate to high





Scheme 46.

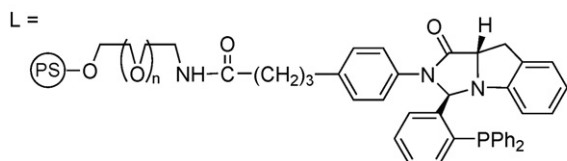
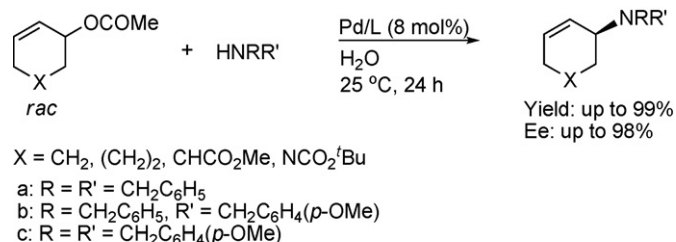


Scheme 47.

yields (63–96%) were achieved with Pd-loading at 1–5 mol% (Scheme 46) [332].

Medium to large size lactones could be successfully synthesized by an intramolecular Tsuji–Trost reaction in high yields in an aqueous biphasic system. An example is shown in Scheme 47, where the *Z*-configured lactone was afforded in 73% yield by Pd-catalysis; the palladium catalyst was made water-soluble by a sulfonated phosphine ligand [333].

Scheme 48 shows an example of asymmetric allylic amination in water, using a chiral P[∞]N ligand bound to an amphiphilic polystyrene–poly(ethylene glycol) resin. Cycloalkenyl carbonates were aminated with dibenzylamines in water at room temperature under heterogeneous conditions to give the cor-



Scheme 48.

responding cycloalkenylamines with high ee (90–98%), with the catalyst being recyclable for up to four times without loss of activity and enantioselectivity [334]. It was noted that the reaction did not take place when performed in an organic solvent, and a very low conversion resulted without the PS–PEG support.

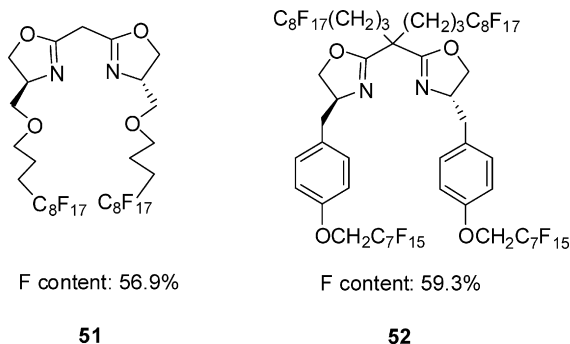
Direct substitution of allyl alcohol by carbon nucleophiles in water [335], or under neat conditions [336], or in an aqueous biphasic medium [337], is also possible. For instance, allyl alcohol reacted with C-nucleophiles in water at 80–100 °C under the catalysis of Pd(PPh₃)/1-adamantanecarboxylic acid [335], or under neat conditions at 70–100 °C by Pd(PPh₃)/acetic acid [336], affording the corresponding allylated products in moderate to high yields. The role of water in the reaction was suggested to be promoting the hydration of the hydroxyl group for the smooth generation of π-allylpalladium species [337]. More recently, palladium-catalyzed allylation of anilines by allylic alcohols in water in the presence of carboxylic acid was reported; allylic anilines were obtained in good yields (up to 99%, including both mono- and di-allylated products) [338].

Transition metal-free Tsuji–Trost reaction in aqueous media have been described as well. Reports by Muzart and co-workers [339,340] demonstrated that allylic substitution of 1-acetoxy-1,3-diphenylpropene by acetylacetone could be achieved in the absence of a metal catalyst in MeOH/H₂O with K₂CO₃ as a base, giving rise to a mixture containing 40% desired product, PhCH(CH(COMe)₂)CH=CHPh; the rest was an ether, PhCH(OMe)CH=CHPh. Mechanistic studies suggested that a stabilized allylic carbocation was involved.

Allylic substitution conducted in ILs has also been reported. For instance, Pd(0)/TPPTS (5 mol%) was shown to catalyze the reaction of allylic acetates with various nucleophiles in [emim]BF₄/H₂O (1/2) with or without base under MW irradiation; excellent yields of the product were obtained together with catalyst recycling for eight times with a consistent activity [341]. Water and TPPTS were essential, with no reaction occurring without either of them. In contrast to the general basic conditions, Bruneau and co-workers [342] recently reported a Ru-catalyzed allylic alkylation of cinnamyl carbonate with different nucleophiles in [Hdmim]PF₆ ([Hdmim] = 1-hexyl-2,3-dimethylimidazolium), which proceeded under neutral conditions at 50 °C, allowing for a very good conversion and

regioselectivity and for high level of recyclability of the solvent/catalyst system.

Fluorous bisoxazoline ligands have been prepared and examined for allylic substitutions by Sinou and co-workers [343,344]. High enantioselectivity could be realized in common solvents and benzotrifluoride, and the catalyst separation could be made easy with such ligand by fluorous extraction following a reaction in common solvents [343]. However, the palladium catalysts derived from these ligands lost activities in fluorous media [344]. In order to circumvent the problem, Sinou and co-workers [345] recently prepared the high-fluorine-content ligands **51** and **52**. When combined with a palladium precursor, in the process of the asymmetric alkylations of *rac*-(*E*)-1,3-diphenylpropenyl acetate with dimethyl malonate in CH_2Cl_2 in the presence of a base (KOAc), ligand **52** led to the desired product in 98% conversion and 92% ee after 24 h, and the catalyst was quantitatively extracted into FC72 after reaction and reused with the same activity and selectivity. In contrast, the less-fluorinated **51** appeared to be less effective under the same reaction conditions, affording only a 39% conversion and 80% ee.

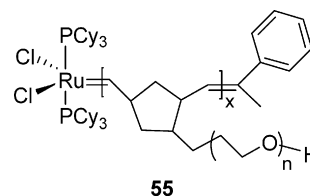


2.4. Olefin metathesis

Olefin metathesis has become a powerful method for C–C bond construction in synthetic organic chemistry with the advent of well-defined catalysts, most notably, the Grubbs ruthenium catalysts [346,347]. Some of these catalysts have been demonstrated to be able to promote ring-opening metathesis polymerization (ROMP) and ring-closing metathesis (RCM) in polar solvents such as water and methanol [348]. However, there is a disadvantage in using the homogeneous catalysts, that is the poor recyclability and the difficulty of separation of catalyst and product. To tackle the problem, the ruthenium catalysts have been immobilized onto support, and then applied to ROMP [349–353] and RCM [354] reactions in water or aqueous phases. For example, Grubbs and co-workers reported the synthesis of a novel ruthenium carbene complex, in which PEG served as a water solubilizing agent, as shown in Scheme 49. The catalyst promoted the ROMP of norbornenes in D_2O and was significantly more active than its unsupported analogue; it could be simply removed by precipitation from the reaction mixture on addition of ether [349,350]. Catalyst **54** [350] in Scheme 49 was more active than the analogous **53** [349], due to the PEG-carbamoyl-benzyl group in the latter limiting the stability of the complex. PEG-supported,

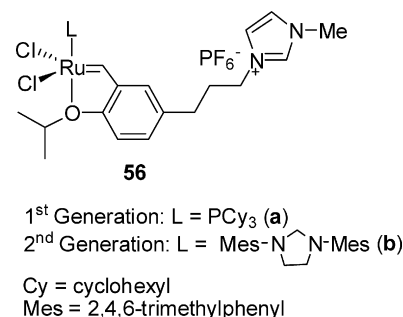
Grubbs's second generation catalyst has been demonstrated to be able to polymerize oxanorbornene to give full conversion in 30 min at room temperature in water at pH 2 or lower [351].

Mini-emulsion polymerization is usually performed to generate small and stable nanoparticles from stable droplets of monomers without the use of surfactants. Héroguez and co-workers [352] disclosed that while the hydrophobic Grubbs catalyst $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CHPh}$ was not appropriate for ROMP of norbornenes in mini-emulsion, the hydrophilic catalyst $\text{RuCl}_3 \cdot x\text{H}_2\text{O}$ showed activity, allowing for the formation of nanoparticles (200–500 nm). However, when the Grubbs catalyst was made hydrophilic by modification with PEO (complex **55**), efficient synthesis of PNB nanoparticles by mini-emulsion ROMP of norbornenes was realized [353].

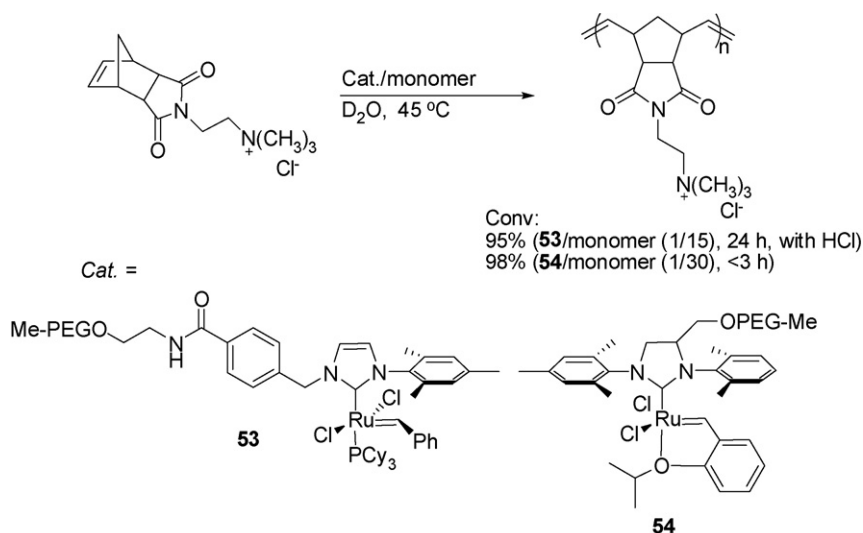


An amphiphilic polymer was employed to anchor the Grubbs–Hoveyda catalyst for the RCM reaction of the benchmark substrate diallylmalonate in water, affording a TON of 390 [354]. Catalyst recovery was affected by extracting the product with pentane from the aqueous reaction mixture; gradual decomposition was noticed during the recycle runs, however.

To conduct olefin metathesis in ILs and to enable easy separation of catalyst from the product, the Grubbs-type catalysts need to be immobilized in the media. This is because solvent extraction would be less effective with the unmodified catalysts, and such catalysts can be more active and selective when resided in the ILs [355]. A more attractive approach is to use ruthenium alkylidenes bearing ionic functionalities, which confer good solubility on the catalyst in the IL phase. Guillemin and co-worker developed imidazolium-tagged Grubbs's first (**56a**) and second (**56b**) generation catalysts, which catalyzed RCM in an IL or IL/organic solvent biphasic mixture. In both cases, a high level of recyclability together with a high activity was obtained [356–358].



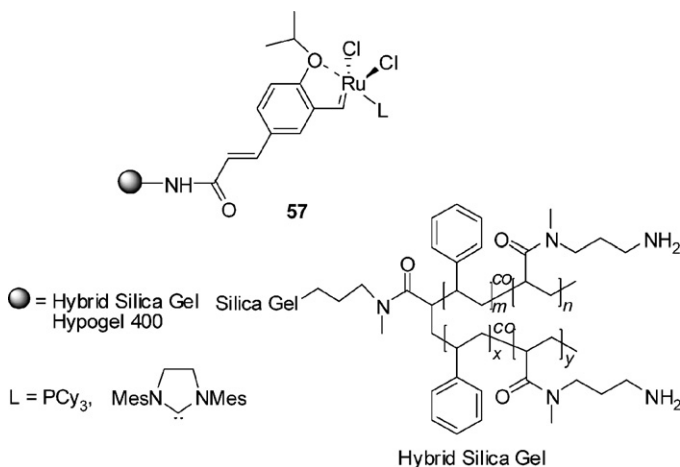
An almost identically tagged, second generation Grubbs–Hoveyda ruthenium carbene complex was reported by Yao et al. [359,360]. The complex was highly active for the RCM of di-, tri- and tetra-substituted diene and enyne



Scheme 49.

substrates in the mixed solvents ($[\text{bmim}]\text{PF}_6/\text{CH}_2\text{Cl}_2$, 1/9). Both the catalyst and IL could be conveniently recycled (up to 17 cycles) with only a slight loss of activity.

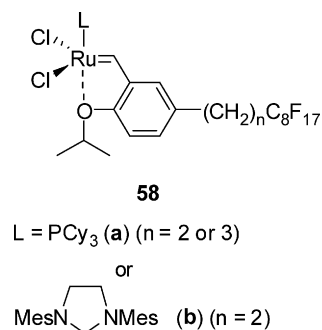
Olefin metathesis conducted in scCO_2 has also been shown to be feasible. In a very recent example, ROMP of norbornene was affected in scCO_2 or a scCO_2/THF mixture using the Grubbs catalyst; the *trans/cis* ratio of the resulting polynorbornenes could be adjusted by varying the amount of the co-solvent THF or of the catalyst [361]. As is known, introduction of perfluoro tags could afford enhanced catalyst solubility in scCO_2 , giving rise to higher reaction rates. However, this also opens up the possibility of leaching the catalyst into the product. To address this issue, Bannwarth and co-workers [362] recently reported the solid-immobilized Hoveyda-type catalysts **57**, which allowed for high yields (up to 95%) of the corresponding products and were recyclable, with a low level of leaching of ruthenium into the product (20 ppm). In contrast, the unsupported catalysts showed higher level of metal leaching.



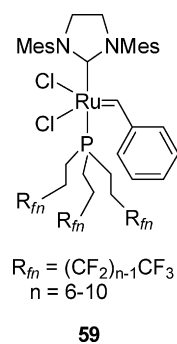
Yao and Zhang also incorporated the second generation Grubbs catalyst into a fluorous polyacrylate polymer [363]. When applied to the fluorous biphasic catalysis of the RCM of dienes, as shown in Scheme 50, the catalyst afforded complete

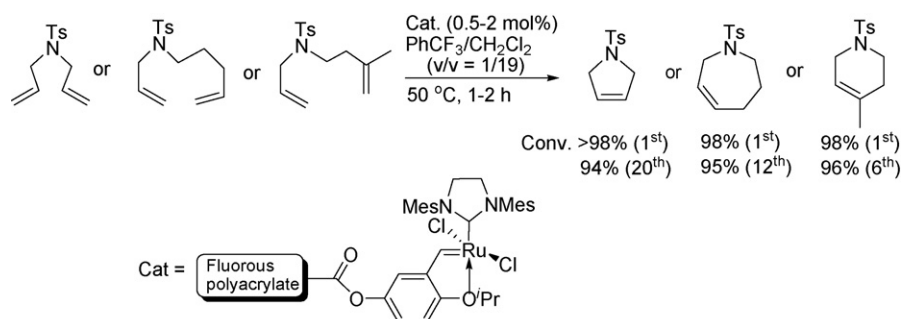
conversion of substrate to product together with easy recycle via FC-72 extraction.

Fluorous tagging was also explored by Curran and co-worker to modify the first and second generation of Grubbs–Hoveyda catalysts [364]. The resulting fluorous catalyst **58** exhibited a similar reactivity profile to the non-fluorous analogues in RCM and cross-metathesis; but the former could be readily recovered by fluorous solid-phase extraction and reused more than five times.



Very recently, Gladysz and co-worker disclosed that the Grubbs' catalyst **59** containing a fluorous phosphine was active for RCM under organic monophasic and fluorous/organic biphasic conditions; however, it was more efficient in the latter case, which was believed to arise from phase transfer of the dissociated fluorous phosphine into the fluorous phase [365].





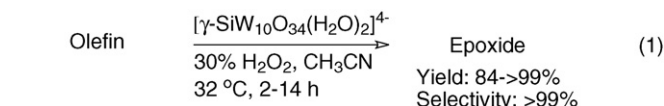
Scheme 50.

2.5. Oxidation

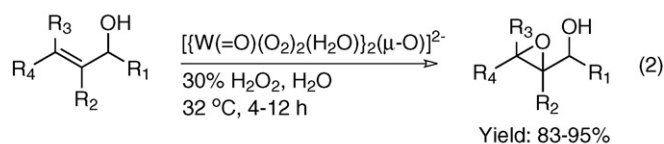
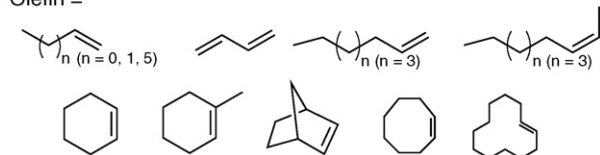
2.5.1. Olefin epoxidation

Olefin epoxidation is one of the main routes for the production of epoxides. Being easily convertible into various bifunctional compounds, epoxides are intermediates for the manufacture of a range of important commercial products. Epoxidation is generally carried out in chlorinated solvents, such as CH₂Cl₂, but has been demonstrated to be practical in the alternative media.

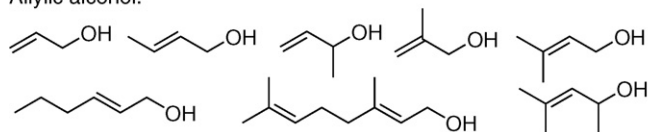
Water is one of the choices as medium for olefin epoxidation. The use of aqueous H₂O₂ has drawn particular attention and this chemistry has been summarized in recent reviews [366,367]. In more recent work, the Mizuno group reported efficient routes for epoxidation of olefins and allylic alcohols with H₂O₂ catalyzed by a silicotungstate [ⁿBu₄N]₄[γ -SiW₁₀O₃₄(H₂O)₂]¹⁴⁻ [368] and a dinuclear peroxotungstate [{W(=O)(O₂)₂(H₂O)}₂(μ -O)]²⁻ [369,370]. Various olefins, including bulky cyclic ones such as cyclooctene or non-activated terminal alkenes such as 1-octene, were epoxidized by 30% H₂O₂ in 84 to >99% yields with \geq 99% selectivity [368], as shown in Eq. (1) of Scheme 51.



Olefin =



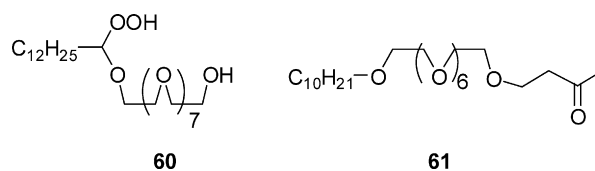
Allylic alcohol:



Scheme 51.

Allylic alcohols were readily oxidized by one equivalent of 30% H₂O₂, with the dinuclear peroxotungstate in high yields and high chemo-, regio- and diastereoselectivities, and with TON and TOF reaching 4200 and 594 h⁻¹, respectively (Eq. (2), Scheme 51) [369,370].

A micellar oxidation system composed of a novel amphiphilic hydroperoxide or ketone has been developed and applied to the epoxidation of water-insoluble substrates in aqueous media without using any surfactant [371,372]. Thus, in the presence of the amphiphilic hydroperoxide **60**, geraniol could be oxidized to 2,3-epoxygeraniol in 85% isolated yield by V₂O₅ in an aqueous KH₂PO₄/NaOH-buffered solution (pH 7.4) at 30 °C [371]. Likewise, in the presence of the ketone **61**, cyclooctene and other olefins such as α,β -unsaturated carbonyl compounds could be converted into the corresponding epoxides by Oxone[®] in moderate to high yields under neutral conditions in water at 5 °C [372].



Biphasic selective epoxidation in a water-organic mixture was also reported [373,374]. Styrene could be epoxidized by 70% aqueous *t*-butyl hydroperoxide (TBHP) catalyzed by K₂Cr₂O₇ or K₂CrO₄ to the oxide with a good selectivity (>60%) and conversion (>50%) in water; the catalyst remained in the aqueous phase, while the reactants and the products resided in the organic phase [373].

Asymmetric epoxidation in water has also been explored. For example, asymmetric epoxidation of allylic alcohols by 70% aqueous TBHP, catalyzed by a vanadium complex in the presence of a bidentate chiral hydroxamic acid, proceeded smoothly to give moderate to high yields (41–92%) and moderate ee's (57–72%); the reaction was shown to be ligand-accelerated [375]. However, the catalytic performance was more effective in toluene than in water. Jørgensen reported an organocatalyst, 2-[bis-(3,5-bis-trifluoromethylphenyl)-trimethylsilyloxy-methyl]-pyrrolidine, which catalyzed the diastereo- and enantioselective asymmetric epoxidation of α,β -unsaturated aldehydes, using H₂O₂ as an oxidant in a water-alcohol solution, affording moderate to good

yields and up to 96% ee of the optically active epoxides [376].

Concerning epoxidation in ILs, a [bmim]PF₆/water biphasic system was shown to be effective for the epoxidation of α,β -unsaturated carbonyl compounds by using H₂O₂ as an oxidant at room temperature [377]. Interestingly, the imidazolium cation was thought to act as a catalyst to transfer OH⁻ out of, and the active species OOH⁻ into, the ionic phase where the epoxidation took place. Epoxidation of electron-poor olefins by aqueous H₂O₂ in a variety of imidazolium ILs [bmim]⁺X⁻ (X⁻ = BF₄⁻, PF₆⁻, CF₃SO₃⁻ and NTf₂⁻) was attempted, and in most cases the alkenes were readily converted into the corresponding epoxides, which could be almost quantitatively extracted from the reaction media by scCO₂ [378]. A significant increase in the reaction rate was observed by addition of a small quantity of water in the reaction mixture. The direct synthesis of styrene carbonate could be realized in moderate yield by means of epoxidation of styrene with TBHP followed by CO₂ cycloaddition to the epoxide in the IL TBAB [379]. The complexes CpMo(CO)₃X or Cp^{*}Mo(CO)₃X (X = Me, Cl) were shown to be effective homogeneous catalysts for epoxidation of olefins in similar ILs. The catalyst performance was found to depend strongly on the water content of the system, with the best performance being seen in a mixture of [bmim]NTf₂/[bmim]PF₆ (4/1) [380].

A novel epoxidation process was very recently reported by Chan, who demonstrated that H₂O₂ can be electrosynthesized from oxygen in a mixture of [bmim]BF₄-H₂O and used *in situ* as oxidant for the epoxidation of electrophilic alkenes. Delivering high yields (up to 92%) of epoxides and requiring only oxygen, water and electricity, the whole process was regarded as an efficient, clean oxidation system [381].

Asymmetric epoxidation can be effected with NaOCl by a Katsuki-type chiral Mn(II)(salen) catalyst in the presence of 4-phenylpyridine *N*-oxide in a [bmim]PF₆-organic solvent biphasic system. The organic solvent, CH₂Cl₂ or ethyl acetate, was necessary as the IL was solid at the reaction temperature of 0 °C [382]. A higher reactivity and comparable ee's were achieved, compared to those obtained in chlorinated solvents.

The dinuclear peroxotungstate [$\{W(=O)(O_2)_2(H_2O)\}_2(\mu-O)]^{2-}$ aforementioned was recently immobilized on an imidazolium IL-modified silica. The resulting catalyst was highly efficient in the epoxidation of various olefins with H₂O₂ as an oxidant in CH₃CN at 100 °C, affording high yields (up to 99%) of the epoxides, together with easy recovery of catalyst by a simple filtration; the catalyst was reused several times without loss of any activity and selectivity [383]. For the epoxidation of *cis*- and *trans*-olefins, the configuration around the C=C double bonds was completely retained in the corresponding epoxides, indicating that free-radical intermediates were not involved.

Epoxidation in scCO₂ and fluorine media has also been investigated in the past. However, recent reports are fewer. An example is seen in the heterogeneous epoxidation of cyclooctene with H₂O₂ catalyzed by Mn-porphyrins embedded in polydimethylsiloxane and organically-modified silicates, in the presence of hexafluoroacetone hydrate (HFAH) as co-catalyst. The oxidation was studied in scCO₂ at 40 °C and

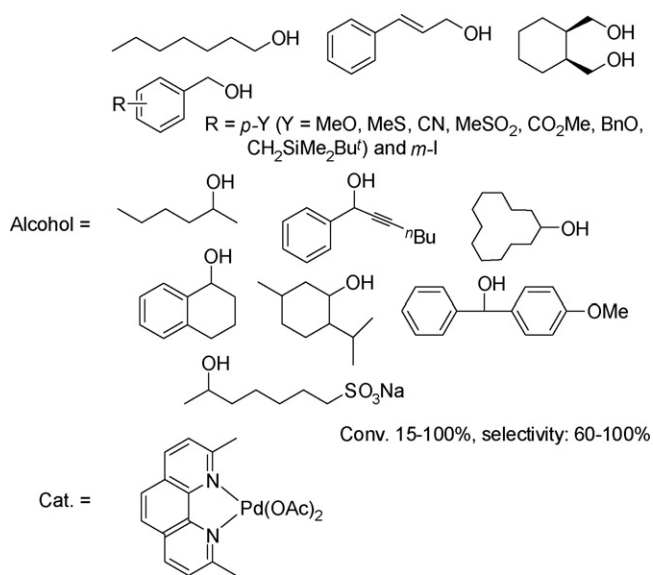
200 bar; complete olefin conversion could be obtained with the formation of cyclooctene oxide as sole product by employing a molar ratio of Mn-porphyrin/substrate/H₂O₂ = 1:400:2000 [384]. The 'sandwich'-type fluorine polyoxometalate (R_FN⁺)₁₂[WZnM₂(H₂O₂)(ZnW₉O₃₄)₂]¹²⁻ (R_FN⁺ = [CF₃(CF₂)₇(CH₂)₃]₃CH₃N⁺) was reported by Neumann and co-workers to be active catalyst for epoxidation of active alkenes such as cyclohexene by aqueous H₂O₂; a lower activity was observed for moderately to weakly nucleophilic alkenes, however [385].

2.5.2. Alcohol oxidation

Selective oxidation of alcohols to the corresponding aldehydes and ketones is one of the most important functional group transformations in modern organic synthesis. The classic methodology is based on stoichiometric heavy metal reagents (*e.g.* Cr, Mn), and commonly uses environmentally undesirable media like chlorinated solvents [386]. As better alternatives, catalytic oxidations with oxidants, such as TBHP, H₂O₂ and oxygen, have been developed [387,388].

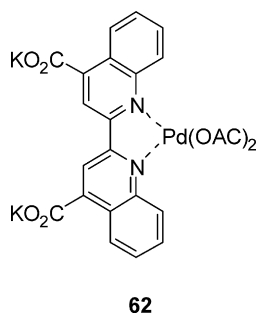
From the viewpoint of green synthesis, water is a best choice to carry out alcohol oxidation, as it could significantly decrease the probability of explosions, eliminate the need for chlorinated solvents, and enable separation and recycling of the catalysts from organic phases. Oxygen, being clean, inexpensive, and readily obtainable, is the oxidant of choice. In pioneering work, Sheldon et al. described the oxidation of various alcohols catalyzed by a water-soluble palladium complex under 30 bar pressure of air, which gave excellent yields of the corresponding carbonyl compounds [389]. Further contributions from the same group concerned similar Pd-catalyzed aerobic oxidations of alcohols in aqueous phase [390–393]. The electronic effects in the (diimine)Pd(II)-catalyzed aerobic oxidation in water/DMSO were investigated; the results showed that both electron-withdrawing substituents on the ligand and electron-donating substituents on the benzyl alcohols favoured a higher reactivity [391]. However, this was not entirely the case for substituted neocuproine-Pd catalysts, where a relatively electron-rich ligand was shown to give the best performance [392]. For instance, as shown in Scheme 52, (neocuproine)Pd(OAc)₂ (0.5 mol%) catalyzed the oxidation of a range of primary and secondary alcohols bearing C=C and C≡C bonds, and halide, α -carbonyl, ether and sulfoxide groups. The catalysis was run in H₂O/DMSO (2/3) at 80 °C with 30 bar of air for 4 h, affording the corresponding aldehydes or ketones in low to excellent yields.

Similar research has been pursued by other groups since then. For instance, water-soluble Pd(II)-biquinoline **62** was reported to be efficient for aerobic oxidation of primary and secondary alcohols in water [394]. With a catalyst loading of 1 mol%, secondary alcohols led to ketones in high yields (85–100%), while aliphatic primary alcohols were fully oxidized to the corresponding acids, and benzyl alcohols were transferred to pure benzoic acid or benzaldehydes with a relatively low amount of acids formed. Earlier, a report by Uozumi and Nakao demonstrated the catalytic oxidation of alcohols in neat water at reflux under atmospheric oxygen, using a novel amphiphilic resin-dispersed



Scheme 52.

nanopalladium catalyst, which provided excellent yields (78 to >99%) of carbonyl compounds with consistency in catalyst recycles [395]. Mechanistic and computational studies disclosed that β -hydride elimination is a rate-determining step in the course of the Pd-catalyzed aerobic alcohol oxidation [396].

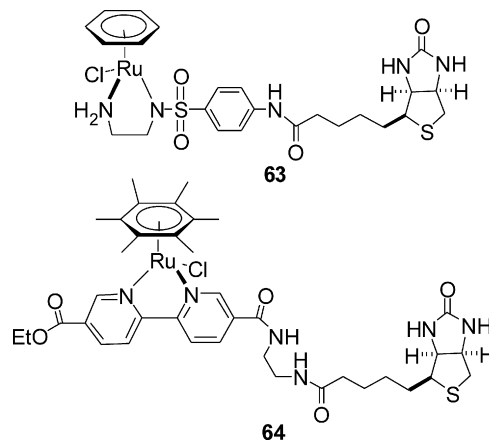


Beside palladium, other transition metal complexes, such as those of Ru [397], Co [398] and Pt/Au [399,400], have been used for aerobic oxidation of alcohols in aqueous phases. For example, water-soluble Ru(II) complexes supported on Dawson-type polyoxometalates, such as $K_8\{(\text{arene})\text{Ru}^{\text{II}}(\text{H}_2\text{O})\}(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})\cdot 12\text{H}_2\text{O}$, could act as a suitable catalyst precursor for the selective oxidation of a wide variety of alcohols with 1 atm of oxygen in a water–alcohol biphasic medium [397]. Microgel-stabilized metal (Pd, Pt and Au) nanoclusters were also efficient (TOF up to 70 h^{-1}) and recoverable catalysts for the selective oxidation of primary and secondary alcohols to the corresponding carbonyl compounds by oxygen in water [399]. Polymer-stabilized gold nanoclusters were successfully applied to the aerobic oxidation of benzylic alcohols in water at ambient temperature; the size of the nanocluster was key to the catalytic activity [400].

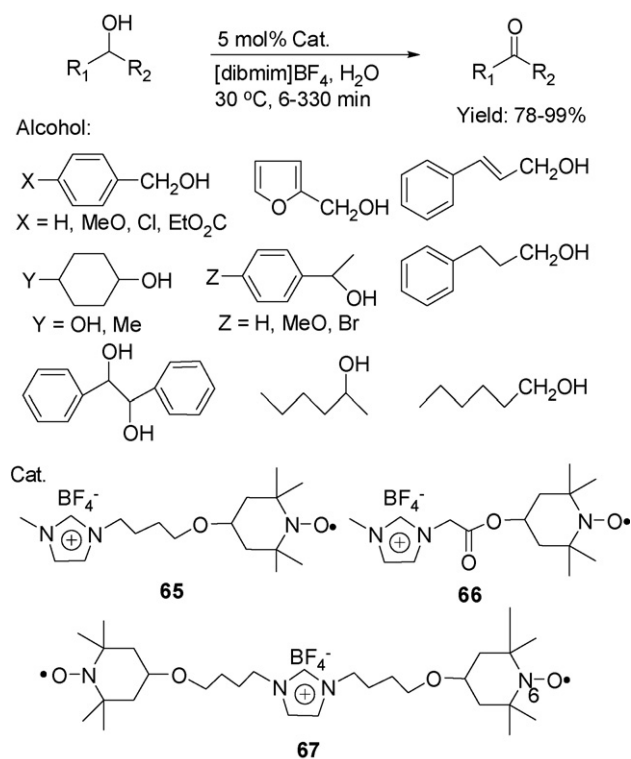
Hydrogen peroxide, particularly in combination with water-soluble polyoxometalates, has been shown to be effective for alcohol oxidation in aqueous biphasic media. Neumann's group has provided good examples in this aspect [401–403]. For

instance, they reported the “sandwich”-type polyoxometalate $\text{Na}_{12}[\text{WZn}_3(\text{H}_2\text{O})_2][\text{ZnW}_9\text{O}_{34}]_2$ to be an efficient and recyclable catalyst for the selective oxidation of various functional groups including diols, pyridine derivatives, amines and aniline derivatives with hydrogen peroxide in a water–alcohol biphasic mixture [403]. Under mild reaction conditions (0.4 mol% catalyst loading, 75°C , 7 h), primary and secondary alcohols were readily oxidized to the corresponding carboxylic acids and ketones, respectively; vicinal alcohols yielded C–C bond cleavage products in excellent yields (>98%); pyridine derivatives were converted into *N*-oxide, and anilines were oxidized to azoxy derivatives or nitro compounds [403]. Extending on Neumann's work, Wang et al. applied mono-substituted Keggin-polyoxometalate complexes to the oxidation of a variety of alcohols in an aqueous/oil biphasic system using hydrogen peroxide as the terminal oxidant [404].

In aqueous phases, TBHP is viable for oxidation of alcohols in the presence of Ru [405,406] or Cu [407,408] complexes. The biotinylated Ru(II)-aminosulfonamide **63** and Ru(II)-bipyridine **64**, developed by Ward and co-workers, were active artificial metalloenzymes for the oxidation of alcohol in water with TBHP as oxidant [405]. A water-soluble copper complex, derived *in situ* from CuCl_2 and the potassium salt of 2,2'-biquinoline-4,4'-dicarboxylic acid, was revealed to be a highly efficient and selective catalyst for the oxidation of secondary benzylic, allylic and propargylic alcohols [407]. More recently, Ajjou and co-workers showed that the catalyst worked for the oxidation of secondary 1-heteroaryl alcohols such as 2-, 3-, 4-pyridines, thiophenes, furans, pyrroles, indoles, imidazoles and thiazole in water with TBHP, affording the corresponding ketones in moderate to excellent yields under mild conditions [408].



TEMPO-mediated (TEMPO = 2,2,6,6-tetramethylpiperidine-1-oxyl) oxidation of alcohols in water has also been reported. The catalytic oxidation of glycerol to ketomalonic acid by TEMPO or silica-gel supported TEMPO proceeded smoothly in water using NaClO/Br^- as the oxidant at pH 10, affording high yields of the desired products, and allowing easy catalyst separation and recycle [409]. In an application of the TEMPO oxidation, carboxylated cellulose nanocrystals were successfully prepared by oxidation of cotton liners and



Scheme 53.

microfibrils of parenchyma cell cellulose; during the reaction the surface primary hydroxyl groups were selectively oxidized to the carboxylic groups [410]. As shown in Scheme 53, TEMPO could be anchored on ionic tags, which proved to be effective for the selective oxidation of various alcohols in water using 1-(4-diacetoxiodobenzyl)-3-methyl imidazolium tetrafluoroborate ([dibmim]BF₄) as an oxidant, with easy catalyst recovery and recycle [411].

Alcohols have been oxidized in ILs. Hypervalent iodine, such as iodoxybenzoic acid (IBX) or Dess-Martin periodinane (DMP) was shown to be a feasible oxidant for the oxidation in both the hydrophilic IL [bmim]Cl in the presence of H₂O [412] or [bmim]BF₄ [413] and the hydrophobic [bmim]PF₆ [413], in which the alcohols underwent smooth oxidation to the corresponding aldehydes or ketones in high yield and selectivity, accompanied with easy recovery and recycle of IL with consistent activity. In [emim]BF₄, the supported hypervalent iodine(III), [dibmim]BF₄, was disclosed to be a more efficient oxidant for the selective oxidation of a variety of primary and secondary alcohols, compared to PhI(OAc)₂; Br⁻ in [emim]BF₄ was proposed to be oxidized to Br⁺ by [dibmim]BF₄, playing a key role in the oxidation [414].

ILs are also suitable solvents for oxidation of alcohols by hydrogen peroxide or molecular oxygen. Catalyzed by a tungstate ion, tris(imidazolium)-tetrakis-(diperoxotungsto)phosphate, a spectrum of primary and secondary alcohols were readily oxidized to the corresponding aldehydes or ketones with H₂O₂ in [bmim]BF₄ at ambient atmosphere in high yield (78–98%); the catalyst could be easily recovered and reused [415]. In [bmim]PF₆, ben-

zylic alcohols, either electron-deficient or -neutral, were selectively oxidized by TEMPO/HBr/H₂O₂ to aldehydes in high yields (81–93%), with both oxidant and IL recovered and reused by simple extraction of products with ether [416]. Similarly, aryl/vinyl/alkyl alcohols were converted to aldehydes by acetamido-TEMPO/Cu(ClO₄)/DMAP (DMAP = dimethylammoniumpyridine) to give high product yields (up to 92% of isolated yield) with efficient catalyst recycle [417].

IL has found use in electro-oxidation as solvent and electrolyte. Benzyl alcohol could be efficiently electro-oxidized to benzaldehyde in a [bmim]BF₄/PF₆-scCO₂ two-phase system under mild conditions [418]. The product could be recovered from the IL by scCO₂ extraction after the electrolysis, allowing the IL to be reused.

scCO₂ has been widely explored as solvent for oxidations, as it could allow for a high mass-transfer rate of substrates and oxidants, such as molecular oxygen, while remaining intact. A systematic investigation in this field has been undertaken by Baiker and Grunwaldt. The oxidation of benzyl alcohol to benzaldehyde with molecular oxygen in scCO₂ over a commercial 0.5 wt.% Pd/Al₂O₃ catalyst was studied in a continuous flow fixed-bed reactor, providing a TOF of 1585 h⁻¹ with a constant selectivity around 95% under optimized reaction conditions (80 °C and 150 bar) [419–422]. Their studies showed that the catalytic performance was affected by various factors, such as temperature, oxygen concentration [419], pressure [420] and solvent [421]. Thus, for example, the TOF increased from 900 to 1800 h⁻¹ when increasing pressure from 140 to 150 bar [419], and from 1500 without toluene to 2500 h⁻¹ with the co-solvent toluene [420]. *In situ* X-ray absorption study (XANES, EXAFS) confirmed that the rate of reaction was a function of oxygen concentration and the Pd surface was only partially oxidized [422].

Beside benzyl alcohol, reports from the same group showed that under optimized reaction conditions, in scCO₂ over Pd/Al₂O₃ with molecular oxygen in a continuous fixed-bed reactor, cinnamyl alcohol was converted to CNA in 60% selectivity and TOF of 400 h⁻¹ [423], geraniol to citral in up to 90% selectivity [424], and 1-phenylethanol to acetophenone in 100% selectivity [425].

In addition to using Pd-based catalysts, a Teflon coated Pt/C catalyst, reported by Tsang and co-workers, displayed high selectivity (>99%) in the oxidation of 9-anthracene methanol to 9-anthracene methanal; both the activity and selectivity were affected by the reaction temperature and pressure [426]. More recently, a silica-supported CrO₃ catalyst was reported to catalyze oxidation of primary and secondary aliphatic alcohols in scCO₂ under continuous flow conditions, giving the corresponding carbonyl compounds in moderate to high yields (46–94%) [427].

FluoRuGel, a fluorinated silica glass doped with tetra-*n*-propylammonium perruthenate (TPAP), was reported to be versatile for the aerobic oxidation of alcohols in scCO₂, affording valuable carbonyl compounds including those which cannot be obtained over supported noble metals, with the catalyst retaining its activity upon prolonged use [428]. A mechanistic study

References

- [1] R.A. Sheldon, *J. Chem. Technol. Biotechnol.* 68 (1997) 381.
- [2] B.M. Trost, *Acc. Chem. Res.* 35 (2002) 695.
- [3] P.T. Anastas, M.M. Kirchhoff, *Acc. Chem. Res.* 35 (2002) 686.
- [4] A.D. Curzons, D.J.C. Constable, D.N. Mortimer, V.L. Cunningham, *Green Chem.* 3 (2001) 1.
- [5] (a) P.G. Jessop, T. Ikariya, R. Noyori, *Science* 269 (1995) 1065;
(b) P.G. Jessop, D.J. Heldebrant, X.W. Li, C.A. Eckert, C.L. Liotta, *Nature* 436 (2005) 231.
- [6] C.J. Li, T.H. Chan, *Organic Reaction in Aqueous Media*, Wiley, New York, 1997.
- [7] F. Joó, *Aqueous Organometallic Catalysis*, Kluwer, Dordrecht, 2001.
- [8] (a) J.D. Holbrey, K.R. Seddon, *J. Chem. Soc. Dalton Trans.* 13 (1999) 2133;
(b) T. Welton, *Chem. Rev.* 99 (1999) 2071;
(c) P. Wasserscheid, W. Keim, *Angew. Chem. Int. Ed.* 39 (2000) 3772;
(d) K.N. Marsh, J.A. Boxall, R. Lichtenthaler, *Fluid Phase Equilibria* 219 (2004) 93;
(e) C.P. Mehnert, *Chem. Eur. J.* 11 (2005) 50.
- [9] L.A. Blanchard, D. Hancu, E.J. Beckman, J.F. Brennecke, *Nature* 399 (1999) 28.
- [10] (a) P.G. Jessop, W. Leitner (Eds.), *Chemical Synthesis using Supercritical Fluids*, Wey-WCH, Weinheim, 1999;
(b) E.J. Beckman, *J. Supercrit. Fluids* 28 (2004) 121.
- [11] (a) I.T. Horváth, J. Rabai, *Science* 266 (1994) 72;
(b) J.A. Gladysz, D.P. Curran, *Tetrahedron* 58 (2002) 3823.
- [12] J. Xiao, in: V.H. Grassian (Ed.), *Environmental Catalysis*, Taylor & Francis, New York, 2005.
- [13] (a) M. Siskin, A.R. Katritzky, *Chem. Rev.* 101 (2001) 825;
(b) N. Akiya, P.E. Savage, *Chem. Rev.* 102 (2002) 2725;
(c) C.J. Li, *Chem. Rev.* 105 (2005) 3095.
- [14] (a) C.M. Gordon, *Appl. Catal. A: Gen.* 222 (2001) 101;
(b) R. Sheldon, *Chem. Commun.* (2001) 2399;
(c) J. Dupont, R.F. de Souza, P.A.Z. Suarez, *Chem. Rev.* 102 (2002) 3667;
(d) D. Zhao, M. Wu, Y. Kou, E.Z. Min, *Catal. Today* 74 (2002) 157;
(e) H. Oliver-Bourbigou, L. Magna, *J. Mol. Catal. A: Chem.* 182–183 (2002) 419;
(f) T. Welton, *Coord. Chem. Rev.* 248 (2004) 2459.
- [15] (a) P.G. Jessop, T. Ikariya, R. Noyori, *Chem. Rev.* 99 (1999) 475;
(b) J.R. Hyde, P. Licence, D. Carter, M. Poliakoff, *Appl. Catal. A: Gen.* 222 (2001) 119;
(c) W. Leitner, *Acc. Chem. Res.* 35 (2002) 746;
(d) P.G. Jessop, F. Joó, C.C. Tai, *Coord. Chem. Rev.* 248 (2004) 2425;
(e) D. Prajapati, M. Gohain, *Tetrahedron* 60 (2004) 85.
- [16] (a) I.T. Horváth, *Acc. Chem. Res.* 31 (1998) 641;
(b) R.H. Fish, *Chem. Eur. J.* 5 (1999) 1677;
(c) G. Poozi, I. Shepperson, *Coord. Chem. Rev.* 242 (2003) 115.
- [17] (a) D. Clarke, M.A. Ali, A.A. Clifford, A. Parratt, P. Rose, D. Schwinn, W. Bannwarth, C.M. Rayner, *Curr. Top. Med. Chem.* 4 (2004) 729;
(b) S.Z. Luo, Y.Y. Peng, B.L. Zhang, P.G. Wang, J.P. Cheng, *Curr. Org. Synth.* 1 (2004) 405;
(c) C.K.Z. Andrade, L.M. Alves, *Curr. Org. Chem.* 9 (2005) 195.
- [18] R.T. Baker, S. Kobayashi, W. Leitner (Eds.), *Adv. Synth. Catal.* 348 (2006) 1317.
- [19] F. Joó, *Acc. Chem. Res.* 35 (2002) 738.
- [20] C. Larpent, R. Dabard, H. Patin, *Tetrahedron Lett.* 28 (1987) 2507.
- [21] D.U. Parmar, S.D. Bhatt, H.C. Bajaj, R.V. Jasra, *J. Mol. Catal. A: Chem.* 202 (2003) 9.
- [22] P.J. Baricelli, G. Rodríguez, A. Rodríguez, E. Lujano, F. López-Linares, *Appl. Catal. A: Gen.* 239 (2003) 25.
- [23] P.J. Baricelli, L. Lzaguirre, J. López, E. Lujano, F. López-Linares, *J. Mol. Catal. A: Chem.* 208 (2004) 67.
- [24] J.M. Gosselin, C. Mercier, G. Allmang, F. Grass, *Organometallics* 10 (1991) 2126.
- [25] Z.Y. Yang, M. Ebihara, T. Kawamura, *J. Mol. Catal. A: Chem.* 158 (2000) 509.
- [26] P. Smolenski, F.P. Pruchnik, Z. Ciunik, T. Lis, *Inorg. Chem.* 42 (2003) 3318.
- [27] D.N. Akbayeva, L. Gonsalvi, W. Oberhauser, M. Peruzzini, F. Vizza, P. Brüggeller, A. Romerosa, G. Sava, A. Bergamo, *Chem. Commun.* (2003) 264.
- [28] S. Bolaño, L. Gonsalvi, F. Zanobini, F. Vizza, V. Bertolasi, A. Romerosa, M. Peruzzini, *J. Mol. Catal. A: Chem.* 224 (2004) 61.
- [29] S. Fujita, Y. Sano, B.M. Bhanage, M. Arai, *J. Catal.* 225 (2004) 95.
- [30] K. Nuihithikul, J.M. Winterbottom, *Chem. Eng. Sci.* 59 (2004) 5439.
- [31] G. Papp, J. Elek, L. Nádasdi, G. Laurenczy, F. Joó, *Adv. Synth. Catal.* 345 (2003) 172.
- [32] J. Joubert, F. Delbecq, *Organometallics* 25 (2006) 854.
- [33] G. Kovács, G. Ujaque, A. Lledós, F. Joó, *Organometallics* 25 (2006) 862.
- [34] (a) F. Joó, J. Kovács, A.C. Bényei, Á. Kathó, *Angew. Chem. Int. Ed.* 37 (1998) 969;
(b) F. Joó, J. Kovács, A.C. Bényei, Á. Kathó, *Catal. Today* 42 (1998) 441.
- [35] F. Joó, M.T. Beck, *React. Kinet. Catal.* 2 (1975) 257.
- [36] N. Makihara, S. Ogo, Y. Watanabe, *Organometallics* 20 (2001) 497.
- [37] H. Gulyás, A.C. Bényei, J. Bakos, *Inorg. Chim. Acta* 357 (2004) 3094.
- [38] H.H. Horváth, F. Joó, *React. Kinet. Catal. Lett.* 85 (2005) 355.
- [39] T.J. Geldbach, G. Laurenczy, R. Scopelliti, P.J. Dyson, *Organometallics* 25 (2006) 733.
- [40] N.K. Singha, S. Bhattacharjee, S. Sivaram, *Rubber Chem. Technol.* 70 (1997) 309.
- [41] L. Wei, J. Jiang, Y. Wang, Z. Jin, *J. Mol. Catal. A: Chem.* 221 (2004) 47.
- [42] S. Macleod, R.J. Rosso, *Adv. Synth. Catal.* 345 (2003) 568.
- [43] V. Kotzabasakis, E. Georgopoulou, M. Pitsikalis, N. Hadjichristidis, G. Papadogianakis, *J. Mol. Catal. A: Chem.* 231 (2005) 93.
- [44] A. Spitaleri, P. Pertici, N. Scalera, G. Vitulli, M. Hoang, T.W. Turney, M. Gleria, *Inorg. Chim. Acta* 352 (2003) 61.
- [45] V. Mévellec, A. Roucoux, *Inorg. Chim. Acta* 357 (2004) 3099.
- [46] C. Daguene, P.J. Dyson, *Catal. Commun.* 4 (2003) 153.
- [47] M.G. Musolino, C.M.S. Cutrupi, A. Donato, D. Pietropaolo, R. Pietropaolo, *J. Mol. Catal. A: Chem.* 195 (2003) 147.
- [48] N.V. Semagina, A.V. Bykov, E.M. Sulman, V.G. Matveeva, S.N. Sidorov, L.V. Dubrovina, P.M. Valetsky, O.I. Kiselyova, A.R. Khokhlov, B. Stein, L.M. Bronstein, *J. Mol. Catal. A: Chem.* 208 (2004) 273.
- [49] N. Semagina, E. Joannet, S. Parra, E. Sulman, A. Renken, L. Kiwi-Minsker, *Appl. Catal. A: Gen.* 280 (2005) 141.
- [50] A. Drelinkiewicz, R. Laitinen, R. Kangas, J. Pursiainen, *Appl. Catal. A: Gen.* 284 (2005) 59.
- [51] F. Omota, A.C. Dimian, A. Bliet, *Appl. Catal. A: Gen.* 293 (2005) 121.
- [52] L. Hegedüs, T. Máthe, *Appl. Catal. A: Gen.* 296 (2005) 209.
- [53] J. Sá, H. Vinek, *Appl. Catal. B: Environ.* 57 (2005) 247.
- [54] D. Gašparovičová, M. Králik, M. Hronec, A. Biffis, M. Zecca, B. Corain, *J. Mol. Catal. A: Chem.* 244 (2005) 258.
- [55] I. Mikami, R. Kitayama, T. Okuhara, *Appl. Catal. A: Gen.* 297 (2006) 24.
- [56] Y. Sakamoto, Y. Kamiya, T. Okuhara, *J. Mol. Catal. A: Chem.* 250 (2006) 80.
- [57] D. Gašparovičová, M. Králik, M. Hronec, A. Biffis, M. Zecca, B. Corain, *J. Mol. Catal. A: Chem.* 244 (2006) 258.
- [58] A. Bényei, F. Joó, *J. Mol. Catal.* 58 (1990) 151.
- [59] S. Ogo, T. Abura, Y. Watanabe, *Organometallics* 21 (2002) 2964.
- [60] S. Ogo, N. Makihara, Y. Watanabe, *Organometallics* 18 (1999) 5470.
- [61] A.N. Ajiou, J.L. Pinet, *J. Mol. Catal. A: Chem.* 214 (2004) 203.
- [62] A. Sharma, V. Kumar, A.K. Sinha, *Adv. Synth. Catal.* 348 (2006) 354.
- [63] A.D. Phillips, S. Bolano, S.S. Bosquain, J.-C. Daran, R. Malacea, M. Peruzzini, R. Poli, L. Gonsalvi, *Organometallics* 25 (2006) 2189.
- [64] K. Raghuraman, N. Pillarsetty, K.R. Prabhu, K.K. Katti, K.V. Katti, *Inorg. Chim. Acta* 357 (2004) 2933.
- [65] Y. Chauvin, L. Mussmann, H. Olivier, *Angew. Chem. Int. Ed.* 34 (1995) 2698.
- [66] P.A.Z. Suarez, J.E.L. Dullius, S. Einloft, R.F. de Souza, J. Dupont, *Polyhedron* 15 (1996) 1217.
- [67] J. Dupont, G.S. Fonseca, A.P. Umpierre, P.F.P. Fichtner, S.P. Teixeira, *J. Am. Chem. Soc.* 124 (2002) 4228.
- [68] G.S. Fonseca, A.P. Umpierre, P.F.P. Fichtner, S.R. Teixeira, J. Dupont, *Chem. Eur. J.* 9 (2003) 3263.

- [69] C.W. Scheeren, G. Machado, J. Dupont, P.F.P. Fichtner, S.R. Teixeira, *Inorg. Chem.* 42 (2003) 4738.
- [70] L.M. Rossi, J. Dupont, G. Machado, P.F.P. Fichtner, C. Radtke, I.J.R. Baumvol, S.R. Teixeira, *J. Braz. Chem. Soc.* 15 (2004) 904.
- [71] E.T. Silverira, A.P. Umpierre, L.M. Rossi, G. Machado, J. Morais, G.V. Soares, I.J.R. Baumvol, S.R. Teixeira, P.F.P. Fichtner, J. Dupont, *Chem. Eur. J.* 10 (2004) 3734.
- [72] L.M. Rossi, G. Machado, P.F.P. Fichtner, S.R. Teixeira, J. Dupont, *Catal. Lett.* 92 (2004) 149.
- [73] A.P. Umpierre, G. Machado, G.H. Fecher, J. Morais, J. Dupont, *Adv. Synth. Catal.* 347 (2005) 1404.
- [74] D. Zhao, P.J. Dyson, G. Laurenczy, J.S. MacIndoe, *J. Mol. Catal. A: Chem.* 214 (2004) 19.
- [75] T. Suárez, B. Fontal, M. Reyes, F. Bellandi, R.R. Contreras, J.M. Ortega, G. León, P. Cancines, B. Castillo, *React. Kinet. Catal. Lett.* 82 (2004) 325.
- [76] D. Xu, Z. Hu, W. Li, S. Luo, Z. Xu, *J. Mol. Catal. A: Chem.* 235 (2005) 137.
- [77] M. Baidossi, A.V. Joshi, S. Mukhopadhyay, Y. Sasson, *Tetrahedron Lett.* 46 (2005) 1885.
- [78] Z. Baán, Z. Finta, G. Keglevich, I. Hermecz, *Tetrahedron Lett.* 46 (2005) 6203.
- [79] A. Lenourry, J.M. Gardiner, G. Stephens, *Biotech. Lett.* 27 (2005) 161.
- [80] E.L.V. Goetheer, A.W. Verkerk, L.J.P. van den Broeke, E. de Wolf, B. Deelman, G. van Koten, J.T.F. Keurentjes, *J. Catal.* 219 (2003) 126.
- [81] F. Zhao, Y. Ikushima, M. Chatterjee, O. Sato, M. Arai, *J. Supercrit. Fluids* 27 (2003) 65.
- [82] S. Fujita, S. Akihara, M. Arai, *J. Mol. Catal. A: Chem.* 249 (2006) 223.
- [83] F. Zhao, Y. Ikushima, M. Arai, *J. Catal.* 224 (2004) 479.
- [84] F. Zhao, S. Fujita, J. Sun, Y. Ikushima, M. Arai, *Catal. Today* 98 (2004) 523.
- [85] F. Zhao, Y. Ikushima, M. Arai, *Catal. Today* 93–95 (2004) 439.
- [86] M. Burgener, R. Furrer, T. Mallant, A. Baiker, *Appl. Catal. A: Gen.* 268 (2004) 1.
- [87] P. Meric, K.M.K. Yu, A.T.S. Kong, S.C. Tsang, *J. Catal.* 237 (2006) 330.
- [88] M. Chatterjee, A. Chatterjee, P. Raveendran, Y. Ikushima, *Green Chem.* 8 (2006) 445.
- [89] N. Hiyoshi, C.V. Rode, O. Sato, M. Shirai, *Appl. Catal. A: Gen.* 288 (2005) 43.
- [90] T. Sato, O. Sato, K. Arai, E. Mine, N. Hiyoshi, C.V. Rode, M. Shirai, *J. Supercrit. Fluids* 37 (2006) 87.
- [91] (a) N. Hiyoshi, T. Inoue, C.V. Rode, O. Sato, M. Shirai, *Catal. Lett.* 106 (2006) 133;
(b) N. Hiyoshi, E. Mine, C.V. Rode, O. Sato, M. Shirai, *Chem. Lett.* 35 (2006) 188.
- [92] H.S. Phiong, F.P. Lucien, A.A. Adesina, *J. Supercrit. Fluids* 25 (2003) 155.
- [93] D. Sinou, D. Maillard, A. Aghmiz, A.M. Masdeu-Bulto, *Adv. Synth. Catal.* 345 (2003) 603.
- [94] K.N. West, J.P. Hallett, R.S. Jones, D. Bush, C.L. Liotta, C.A. Eckert, *Ind. Eng. Chem. Res.* 43 (2004) 4827.
- [95] D. Sinou, in: B. Corlins, W.A. Herrman (Eds.), *Aqueous-phase Organometallic Catalysis*, Wiley-VCH, Weinheim, 1998.
- [96] T. Dwars, G. Oehme, *Adv. Synth. Catal.* 344 (2002) 239.
- [97] A. Wolfson, I.F.J. Vankelecom, S. Geresh, P.A. Jacobs, *J. Mol. Catal. A: Chem.* 198 (2003) 39.
- [98] T.V. RajanBabu, Y. Yan, S. Shin, *J. Am. Chem. Soc.* 123 (2001) 10207.
- [99] A. Wolfson, I.F.J. Vankelecom, P.A. Jacobs, *Tetrahedron Lett.* 46 (2005) 2513.
- [100] M. Berthod, C. Saluzzo, C. Mignani, M. Lemaire, *Tetrahedron: Asymm.* 15 (2004) 639.
- [101] M. Berthod, G. Mignani, M. Lemaire, *J. Mol. Catal. A: Chem.* 233 (2005) 105.
- [102] L. Bartek, M. Drobek, M. Kuzma, P. Kluson, L. Cerveny, *Catal. Commun.* 6 (2005) 61.
- [103] R. Hoen, S. Leleu, P.N.M. Botman, V.A.M. Appelman, B.L. Feringa, H. Hiemstra, A.J. Minnaard, J.H. van Maarseveen, *Org. Bio. Chem.* 4 (2006) 613.
- [104] B. Pugin, V. Groehn, R. Moser, H.-U. Blaser, *Tetrahedron: Asymm.* 17 (2006) 544.
- [105] F.T. Jere, D.J. Miller, J.E. Jackson, *Org. Lett.* 5 (2003) 527.
- [106] F.T. Jere, J.E. Jackson, D.J. Miller, *Ind. Eng. Chem. Res.* 43 (2004) 3297.
- [107] G. Oehme, I. Grassert, E. Paetzold, H. Fuhrmann, T. Dwars, U. Schmidt, I. Iovel, *Kinet. Catal.* 44 (2003) 766.
- [108] V. Mévellec, C. Mattioda, J. Schulz, J.P. Rolland, A. Roucoux, *J. Catal.* 225 (2004) 1.
- [109] (a) S. Hashiguchi, A. Fujii, J. Takehara, T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* 117 (1995) 7652;
(b) A. Fuji, S. Hashiguchi, N. Uematsu, T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* 118 (1996) 2521.
- [110] X. Wu, X. Li, W. Hems, F. King, J. Xiao, *Org. Biomol. Chem.* 2 (2004) 1818.
- [111] X. Wu, D. Vinci, T. Ikariya, J. Xiao, *Chem. Commun.* (2005) 4447.
- [112] J. Xiao, X. Wu, A. Zanotti-Gerosa, F. Hancock, *Chim. Oggi-Chem. Today* 23 (2005) 50.
- [113] X. Li, J. Blacker, I. Houson, X. Wu, J. Xiao, *Synlett* 8 (2006) 1155.
- [114] T. Thorpe, J. Blacker, S.M. Brown, C. Bubert, J. Crosby, S. Fitzjohn, J.P. Muxworthy, J.M.J. Williams, *Tetrahedron Lett.* 42 (2001) 4037.
- [115] Y.P. Ma, H. Liu, L. Chen, X. Cui, J. Zhu, J.G. Deng, *Org. Lett.* 5 (2003) 2103.
- [116] J.S. Wu, F. Wang, Y.P. Ma, X. Cui, L.F. Cun, J. Zhu, J.G. Deng, B.L. Yu, *Chem. Commun.* 2006 (1766).
- [117] X. Wu, X. Li, F. King, J. Xiao, *Angew. Chem. Int. Ed.* 44 (2005) 3407.
- [118] J. Mao, B. Wan, F. Wu, S. Lu, *Tetrahedron Lett.* 46 (2005) 7341.
- [119] X. Wu, X. Li, M. McConville, O. Saidi, J. Xiao, *J. Mol. Catal.* 247 (2006) 153.
- [120] C. Letondor, N. Humbert, T.R. Ward, *Proc. Natl. Acad. Sci.* 102 (2005) 4683.
- [121] X. Li, W. Chen, W. Hems, F. King, J. Xiao, *Tetrahedron Lett.* 45 (2004) 951.
- [122] X. Li, X. Wu, W. Chen, F.E. Hancock, F. King, J. Xiao, *Org. Lett.* 6 (2004) 3321.
- [123] P. Liu, J. Deng, Y. Tu, S. Wang, *Chem. Commun.* (2004) 2070.
- [124] P. Liu, P. Gu, J. Deng, Y. Tu, Y. Ma, *Eur. J. Org. Chem.* (2005) 3221.
- [125] Y. Arakawa, N. Haraguchi, S. Itsuno, *Tetrahedron Lett.* 47 (2006) 3239.
- [126] Y. Zhu, K. Carpenter, C. Ching, S. Bahnmüller, P. Chan, *Angew. Chem. Int. Ed.* 42 (2003) 3792.
- [127] H.L. Ngo, A. Hu, W. Lin, *Tetrahedron Lett.* 46 (2005) 595.
- [128] W. Xiong, Q. Lin, H. Ma, H. Zheng, H. Chen, X. Li, *Tetrahedron: Asymm.* 16 (2005) 1959.
- [129] T.J. Geldbatch, M.R.H. Brown, R. Scopelliti, P.J. Dyson, *J. Organomet. Chem.* 690 (2005) 5055.
- [130] H.L. Ngo, A. Hu, W. Lin, *Chem. Commun.* (2003) 1912.
- [131] A. Hu, H.L. Ngo, W. Lin, *Angew. Chem. Int. Ed.* 43 (2004) 2501.
- [132] M. Berthod, J.M. Joerger, G. Mignani, M. Vaultier, M. Lemaire, *Tetrahedron: Asymm.* 15 (2004) 2219.
- [133] E.V. Starodubstseva, M.G. Vinogradov, V.A. Pavlov, L.S. Gorshkova, V.A. Ferapontov, *Russ. Chem. Bull. Int. Ed.* 53 (2004) 2172.
- [134] A. Wolfson, I.F.J. Vankelecom, P.A. Jacobs, *J. Organomet. Chem.* 690 (2005) 3558.
- [135] M. Solinas, A. Pfltz, P.G. Cozzi, W. Leitner, *J. Am. Chem. Soc.* 126 (2004) 16142.
- [136] R. Giernoth, M.S. Krumm, *Adv. Synth. Catal.* 346 (2004) 989.
- [137] S. Lee, Y. Zhang, J. Piao, H. Yoon, C. Song, J. Choi, J. Hong, *Chem. Commun.* (2003) 2624.
- [138] B. Pugin, M. Studer, E. Kuesters, G. Sedelmeier, X. Feng, *Adv. Synth. Catal.* 346 (2004) 1481.
- [139] T. Fráter, L. Gubicza, Á. Szöllösy, J. Bakos, *Inorg. Chim.* 359 (2006) 2756.
- [140] K.L. Boyle, E.B. Lipsky, C.S. Kalberg, *Tetrahedron Lett.* 47 (2006) 1311.
- [141] T.J. Geldbatch, P.J. Dyson, *J. Am. Chem. Soc.* 126 (2004) 8114.
- [142] I. Kawasaki, K. Tsunoda, T. Tsuji, T. Yamaguchi, H. Shibuta, N. Uchida, M. Yamashita, S. Ohta, *Chem. Commun.* (2005) 2134.

- [143] J. Xiao, S.C.A. Nefkens, P.G. Jessop, T. Ikariya, R. Noyori, *Tetrahedron* 37 (1996) 2813.
- [144] M. Berthod, G. Mignani, M. Lemaire, *Tetrahedron: Asymm.* 15 (2004) 1121.
- [145] X. Dong, C. Erkey, *J. Mol. Catal. A: Chem.* 211 (2004) 73.
- [146] D.J. Adams, W. Chen, E.G. Hope, S. Lange, A.M. Stuart, A. West, J. Xiao, *Green Chem.* 5 (2003) 118.
- [147] B. Cornlis, W.A. Herrmann (Eds.), *Applied Homogeneous Catalysis with Organometallic Compounds*, Wiley-VCH, Weinheim, Germany, 1996.
- [148] D. Prajapati, M. Gohain, *Tetrahedron* 60 (2004) 815.
- [149] D.U. Parmar, H.C. Bajai, R.V. Jasra, B.M. Moros, V.A. Likhohobov, *J. Mol. Catal. A: Chem.* 211 (2004) 83.
- [150] P.J. Baricelli, E. Lujano, M. Rodríguez, A. Fuentes, R.A. Sánchez-Delgado, *Appl. Catal. A: Chem.* 263 (2004) 187.
- [151] P.J. Baricelli, E. Lujano, M. Modroño, A.C. Marrero, Y.M. Garaña, A. Fuentes, R.A. Sánchez-Delgado, *J. Organomet. Chem.* 689 (2004) 3782.
- [152] J.T. Sullivan, J. Sadula, B.E. Hanson, R.J. Rosso, *J. Mol. Catal. A: Chem.* 214 (2004) 213.
- [153] P.J. Baricelli, K. Segovia, E. Lujano, M. Modroño-Alonso, F. López-Linares, R.A. Sánchez-Delgado, *J. Mol. Catal. A: Chem.* 252 (2006) 70.
- [154] X. Wang, H.Y. Fu, X. Li, H. Chen, *Catal. Commun.* 5 (2004) 739.
- [155] A.H.G. Gent, D.W.F. Briman, G.F. Versteeg, *Ind. Eng. Chem. Res.* 43 (2004) 7465.
- [156] P.J. Baricelli, R. Santos, E. Lujano, A.J. Pardey, *J. Mol. Catal. A: Chem.* 207 (2004) 83.
- [157] L. Wang, H. Chen, Y. He, Y. Li, M. Li, X. Li, *Appl. Catal. A: Gen.* 242 (2003) 85.
- [158] H. Chen, Y. Li, R. Li, P. Cheng, X. Li, *J. Mol. Catal. A: Chem.* 198 (2003) 1.
- [159] M. Li, Y. Li, H. Chen, X. Li, *J. Mol. Catal. A: Chem.* 194 (2003) 13.
- [160] M. Li, H. Fu, M. Yang, H. Zheng, Y. He, H. Chen, X. Li, *J. Mol. Catal. A: Chem.* 235 (2005) 130.
- [161] H.J.V. Barros, B.E. Hanson, E.V. Gusevskaya, E.N. dos Santos, *Appl. Catal. A: Gen.* 278 (2004) 57.
- [162] Q. Peng, X. Liao, Y. Yuan, *Catal. Commun.* 5 (2004) 447.
- [163] C. Liu, J. Jiang, Y. Wang, F. Cheng, Z. Jin, *J. Mol. Catal. A: Chem.* 198 (2003) 23.
- [164] X. Liu, F. Kong, X. Zheng, Z. Jin, *Catal. Commun.* 4 (2003) 129.
- [165] M.T. Zarka, M. Bortenschlager, K. Wurst, O. Nuyken, R. Weberskirch, *Organometallics* 23 (2004) 4817.
- [166] E. Paetzold, G. Oehme, C. Fischer, M. Frank, *J. Mol. Catal. A: Chem.* 200 (2003) 95.
- [167] T. Mathivet, C. Méliet, Y. Castanet, A. Mortreux, L. Caron, S. Tilloy, E. Monflier, *J. Mol. Catal. A: Chem.* 176 (2001) 105.
- [168] L. Leclercq, M. Sauthier, Y. Castanet, A. Mortreux, H. Bricout, E. Monflier, *Adv. Synth. Catal.* 347 (2005) 55.
- [169] L. Leclercq, F. Hapiot, S. Tilloy, K. Ramkisoensing, J.N.H. Reek, P.W.N.M. van Leeuwen, E. Monflier, *Organometallics* 24 (2005) 2070.
- [170] B. Sueur, L. Leclercq, M. Sauthier, Y. Castanet, A. Mortreux, H. Bricout, S. Tilloy, E. Monflier, *Chem. Eur. J.* 11 (2005) 6228.
- [171] D. Kirschner, T. Green, F. Hapiot, S. Tilloy, L. Leclercq, H. Bricout, E. Monflier, *Adv. Synth. Catal.* 348 (2006) 379.
- [172] S. Tilloy, G. Crowyn, E. Monflier, P.W.N.M. van Leeuwen, J.N.H. Reek, *New J. Chem.* 30 (2006) 377.
- [173] R. Abu-Reziq, J. Blum, D. Avnir, *Chem. Eur. J.* 10 (2004) 958.
- [174] R. Abu-Reziq, D. Avnir, J. Blum, *Angew. Chem. Int. Ed.* 41 (2002) 4132.
- [175] M. Haumann, H. Koch, R. Schomäcker, *Catal. Today* 79–80 (2003) 43.
- [176] C.C. Miyagawa, J. Kupka, A. Schumpe, *J. Mol. Catal. A: Chem.* 234 (2005) 9.
- [177] R. Abu-Reziq, D. Avnir, J. Blum, *Eur. J. Org. Chem.* (2005) 3640.
- [178] H. Klein, R. Jackstell, M. Beller, *Chem. Commun.* (2005) 2283.
- [179] Z. Li, Q. Peng, Y. Yuan, *Appl. Catal. A: Gen.* 239 (2003) 79.
- [180] M. Benaissa, U.J. Jáuregui-Haza, I. Nikov, A.M. Wilhelm, H. Delmas, *Catal. Today* 79–80 (2003) 419.
- [181] H. Zhu, Y. Ding, H. Yin, L. Yan, J. Xiong, Y. Lu, H. Luo, L. Lin, *Appl. Catal. A: Gen.* 245 (2003) 111.
- [182] C. Disser, C. Muennich, G. Luft, *Appl. Catal. A: Gen.* 296 (2005) 201.
- [183] S.M. Silva, R.P. Bronger, Z. Freixa, J. Dupont, P.W.N.M. van Leeuwen, *New J. Chem.* 27 (2003) 1294.
- [184] C.P. Mehnert, R.A. Cook, N.C. Dispenziere, E.J. Mozeleski, *Polyhedron* 23 (2004) 2679.
- [185] Q. Lin, H.Y. Fu, F. Xue, M.L. Yuan, H. Chen, X.J. Li, *Acta Phys. Chem. Sinica* 22 (2006) 465.
- [186] A. Riisager, P. Wasserscheid, R. van Hal, R. Fehrmann, *J. Mol. Catal.* 219 (2003) 452.
- [187] A. Riisager, R. Fehrmann, S. Flicker, R. van Hal, M. Haumann, P. Wasserscheid, *Angew. Chem. Int. Ed.* 44 (2005) 815.
- [188] A. Riisager, R. Fehrmann, M. Haumann, B.S.K. Gorbe, P. Wasserscheid, *Ind. Eng. Chem. Res.* 44 (2005) 9853.
- [189] Y. Yang, C. Deng, Y. Yuan, *J. Catal.* 232 (2005) 108.
- [190] A. Riisager, B. Jørgensen, P. Wasserscheid, R. Fehrmann, *Chem. Commun.* (2006) 994.
- [191] F. Shi, J. Peng, Y. Deng, *J. Mol. Catal.* 219 (2003) 372.
- [192] W. Wojtkow, A.M. Trzeciak, R. Choukroun, J.L. Pellegatta, *J. Mol. Catal. A: Chem.* 224 (2004) 81.
- [193] A. Balázs, C. Benedek, S. Törös, *J. Mol. Catal. A: Chem.* 244 (2005) 105.
- [194] G. Rangits, L. Kollár, *J. Mol. Catal. A: Chem.* 246 (2006) 59.
- [195] Y.Y. Wang, M.M. Luo, Q. Lin, H. Chen, X.J. Li, *Green Chem.* 8 (2006) 545.
- [196] X. Zhao, H. Alper, Z. Yu, *J. Org. Chem.* 71 (2006) 3988.
- [197] P.B. Webb, M.F. Sellin, T.E. Kunene, S. Williamson, A.M.Z. Slawin, D.J. Cole-Hamilton, *J. Am. Chem. Soc.* 125 (2003) 15577.
- [198] S. Fujita, S. Fujisawa, B.M. Bhanage, M. Arai, *Tetrahedron Lett.* 45 (2004) 1307.
- [199] S. Fujita, S. Fujisawa, B.M. Bhanage, Y. Ikushima, M. Arai, *Eur. J. Chem.* (2004) 2881.
- [200] M. Solinas, J. Jiang, O. Stelzer, W. Leitner, *Angew. Chem. Int. Ed.* 44 (2005) 2291.
- [201] H. Jin, B. Subramaniam, *Chem. Eng. Sci.* 59 (2004) 4887.
- [202] A.R. Tadd, A. Marteel, M.R. Mason, J.A. Davies, M.A. Abraham, *J. Supercrit. Fluids* 25 (2003) 183.
- [203] A. Marteel, J.A. Davies, M.R. Mason, T. Tack, S. Bektsev, M.A. Abraham, *Catal. Commun.* 4 (2003) 309.
- [204] S. Bektsev, T. Tack, M.R. Mason, M.A. Abraham, *Ind. Eng. Chem. Res.* 44 (2005) 4973.
- [205] I. Kani, R. Flores Jr., J.P. Fackler, A. Akgerman, *J. Supercrit. Fluids* 31 (2004) 287.
- [206] R.P.J. Bronger, J.P. Bermon, J.N.H. Reek, P.C.J. Kamer, P.W.N.M. van Leeuwen, D.N. Carter, P. Licence, M. Poliakkoff, *J. Mol. Catal. A: Chem.* 224 (2004) 145.
- [207] D.J. Adams, D.J. Cole-Hamilton, E.G. Hope, P.J. Pogorzelec, A.M. Stuart, *J. Organomet. Chem.* 689 (2004) 1413.
- [208] A. Aghmiz, C. Claver, A.M. Masdeu-Bultó, D. Maillard, D. Sinou, *J. Mol. Catal. A: Chem.* 208 (2004) 97.
- [209] Y. Huang, E. Perperi, G. Manos, D.J. Cole-Hamilton, *J. Mol. Catal. A: Chem.* 210 (2004) 17.
- [210] E. Perperi, Y. Huang, P. Angeli, G. Manos, C.R. Mathison, D.J. Cole-Hamilton, D.J. Adama, E.G. Hope, *Chem. Eng. Sci.* 59 (2004) 4983.
- [211] E. Perperi, Y. Huang, P. Angeli, G. Manos, D.J. Cole-Hamilton, *J. Mol. Catal. A: Chem.* 221 (2004) 19.
- [212] F. Alonso, I.P. Beletskaya, M. Yus, *Tetrahedron* 61 (2005) 11771.
- [213] N.A. Bumagin, P.G. More, I.P. Beletskaya, *J. Organomet. Chem.* 371 (1989) 397.
- [214] C. Nájera, J. Gil-Molto, S. Karlström, L.R. Falvello, *Org. Lett.* 5 (2003) 1451.
- [215] J. Hou, L. Yang, X. Cui, Y. Wu, *Chin. J. Chem.* 21 (2003) 717.
- [216] J. Gil-Moltó, S. Karlström, C. Nájera, *Tetrahedron* 61 (2005) 12168.
- [217] L. Botella, C. Nájera, *Tetrahedron* 60 (2004) 5563.
- [218] L. Botella, C. Nájera, *Tetrahedron Lett.* 45 (2004) 1833.
- [219] L. Botella, C. Nájera, *J. Org. Chem.* 70 (2005) 4360.
- [220] C. Nájera, L. Botella, *Tetrahedron* 61 (2005) 9688.
- [221] P. Nisson, M. Larhed, A. Hallberg, *J. Am. Chem. Soc.* 125 (2003) 3430.
- [222] A. Svennebring, P. Nilsson, M. Larhed, *J. Org. Chem.* 69 (2004) 3345.
- [223] S. Bhattacharya, A. Srivastava, S. Sengupta, *Tetrahedron Lett.* 46 (2005) 3557.

- [224] Z. Zhang, Z. Zha, C. Gan, C. Pan, Y. Zhou, Z. Wang, M. Zhou, J. Org. Chem. 71 (2006) 4339.
- [225] L.R. Moore, K.H. Shaughnessy, Org. Lett. 6 (2004) 225.
- [226] R.B. de Vasher, L.R. Moore, K.H. Shaughnessy, J. Org. Chem. 69 (2004) 7919.
- [227] C. Rabeyrin, D. Sinou, J. Mol. Catal. A: Chem. 215 (2004) 89.
- [228] Y. Niu, R.M. Crooks, C.R. Chime 6 (2003) 1049.
- [229] A. Perosa, P. Tundo, M. Selva, S. Zinovyev, A. Testa, Org. Biomol. Chem. 2 (2004) 2249.
- [230] Z. Wang, B. Shen, A. Zou, N. He, Chem. Eng. J. 113 (2005) 27.
- [231] H. Hagiwara, Y. Sugawara, T. Hoshi, T. Suzuki, Chem. Commun. (2005) 2942.
- [232] Y.M.A. Yamada, K. Takeda, H. Takahashi, S. Ikegami, Tetrahedron 60 (2004) 4097.
- [233] G.W. Kabalka, G. Dong, B. Venkataiah, Tetrahedron Lett. 45 (2004) 2775.
- [234] S.T. Handy, M. Okello, G. Dickenson, Org. Lett. 5 (2003) 2513.
- [235] S.T. Handy, M. Okello, Tetrahedron Lett. 44 (2003) 8395.
- [236] D.A. Gerritsma, A. Robertson, J. McNulty, A. Capretta, Tetrahedron Lett. 45 (2004) 7629.
- [237] X. Xie, B. Chen, J. Lu, J. Han, X. She, X. Pan, Tetrahedron Lett. 45 (2004) 6235.
- [238] G. Zou, Z. Wang, J. Zhu, J. Tang, M. He, J. Mol. Catal. A: Chem. 206 (2003) 193.
- [239] (a) S.A. Forsyth, H.Q.N. Gunaratne, C. Hardacre, A. McKeown, D.W. Rooney, K.R. Seddon, J. Mol. Catal. A: Chem. 231 (2005) 61;
(b) S.A. Forsyth, H.Q.N. Gunaratne, C. Hardacre, A. McKeown, D.W. Rooney, Org. Process Res. Dev. 10 (2006) 94.
- [240] C.C. Cassol, A.P. Umpierre, G. Machado, S.I. Wolke, J. Dupont, J. Am. Chem. Soc. 127 (2005) 3298.
- [241] V. Caló, A. Nacci, A. Monopoli, A. Detomaso, P. Iliade, Organometallics 22 (2003) 4193.
- [242] V. Caló, A. Nacci, A. Monopoli, A. Fornaro, L. Sabbatini, N. Cioffi, N. Ditaranto, Organometallics 23 (2004) 5154.
- [243] V. Caló, A. Nacci, A. Monopoli, E. Leva, N. Cioffi, Org. Lett. 7 (2005) 617.
- [244] X. Xie, J. Lu, B. Chen, J. Han, X. She, X. Pan, Tetrahedron Lett. 45 (2004) 809.
- [245] S. Park, H. Alper, Org. Lett. 5 (2003) 3209.
- [246] V. Caló, A. Nacci, A. Monopoli, S. Laera, N. Cioffi, J. Org. Chem. 68 (2003) 2929.
- [247] J.-C. Xiao, B. Twamley, J.M. Shreeve, Org. Lett. 6 (2004) 3845.
- [248] C. Jin, B. Twamley, J.M. Shreeve, Organometallics 24 (2005) 3020.
- [249] R. Wang, M.M. Piekarski, J.M. Shreeve, Org. Biol. Chem. 4 (2006) 1878.
- [250] G. Zou, W. Huang, Y. Xiao, J. Tang, New J. Chem. 30 (2006) 803.
- [251] S. Liu, T. Fukuyama, M. Sato, I. Ryu, Synlett (2004) 1814.
- [252] S. Liu, T. Fukuyama, M. Sato, I. Ryu, Org. Process Res. Dev. 8 (2004) 477.
- [253] L. Xu, W. Chen, J. Ross, J. Xiao, Org. Lett. 3 (2001) 295.
- [254] L. Xu, J. Mo, C. Baillie, J. Xiao, J. Organomet. Chem. 687 (2003) 301.
- [255] J. Mo, L. Xu, J. Xiao, J. Am. Chem. Soc. 127 (2005) 751.
- [256] W. Pei, J. Mo, J. Xiao, J. Organomet. Chem. 690 (2005) 3546.
- [257] J. Mo, S. Liu, J. Xiao, Tetrahedron 61 (2005) 9902.
- [258] J. Mo, J. Xiao, Angew. Chem. Int. Ed. 45 (2006) 4152.
- [259] J. Mo, L. Xu, J. Ruan, S. Liu, J. Xiao, Chem. Commun. (2006) 3591.
- [260] S. Liu, J. Xiao, unpublished results.
- [261] S. Liu, N. Berry, N. Thomson, A. Pettman, J. Mo, J. Xiao, J. Org. Chem. 71 (2006) 7467.
- [262] M.A. Carroll, A.B. Holmes, Chem. Commun. (1998) 1395.
- [263] D.K. Morita, D.R. Psiri, S.A. David, W.H. Glaze, W. Tumas, Chem. Commun. (1998) 1397.
- [264] B.M. Bhanage, Y. Ikushima, M. Shirai, M. Arai, Tetrahedron Lett. 40 (1999) 6427.
- [265] B.M. Bhanage, S. Fujita, M. Arai, J. Organomet. Chem. 687 (2003) 211.
- [266] C. Rocaboy, J.A. Gladysz, New J. Chem. 27 (2003) 39.
- [267] D.P. Curran, K. Fischer, G. Moura-Letts, Synlett (2004) 1379.
- [268] K.S.A. Vallin, Q. Zhang, M. Larhed, D.P. Curran, A. Hallberg, J. Org. Chem. 68 (2003) 6639.
- [269] Y. Nakamura, S. Takeuchi, Y. Ohgo, J. Fluorine Chem. 120 (2003) 121.
- [270] J. Bayardon, M. Cavazzini, D. Maillard, G. Pozzi, S. Quici, D. Sinou, Tetrahedron Asymm. 14 (2003) 2215.
- [271] T. Fukuyama, M. Arai, H. Matsubara, I. Ryu, J. Org. Chem. 69 (2004) 8105.
- [272] N.E. Leadbeater, Chem. Commun. (2005) 2881.
- [273] R. Franzen, Y. Xu, Can. J. Chem. -Rev. Canadienne Chim. 83 (2005) 266.
- [274] A. Arcadi, G. Cerichelli, M. Chiarini, M. Correa, D. Zorzan, Eur. J. Org. Chem. (2003) 4080.
- [275] G. Lu, R. Franzén, Q. Zhang, Y. Xu, Tetrahedron Lett. 46 (2005) 4255.
- [276] B.P. Bandgar, S.V. Bettigeri, J. Phopase, Tetrahedron Lett. 45 (2004) 6959.
- [277] L. Liu, Y. Zhang, B. Xin, J. Org. Chem. 71 (2006) 3994.
- [278] D.N. Korolev, N.A. Bumagin, Russ. Chem. Bull. Int. Ed. 53 (2004) 364.
- [279] C.M. Crudden, M. Sateesh, R. Lewis, J. Am. Chem. Soc. 127 (2005) 10045.
- [280] L. Artok, H. Bulut, Tetrahedron Lett. 45 (2004) 3881.
- [281] K. Shimizu, R. Maruyama, S. Komai, T. Kodama, Y. Kitayama, J. Catal. 227 (2004) 202.
- [282] J.K. Cho, R. Najman, T.W. Dean, O. Ichihara, C. Muller, M. Bradley, J. Am. Chem. Soc. 128 (2006) 6276.
- [283] N.E. Leadbeater, M. Macro, Angew. Chem. Int. Ed. 42 (2003) 1407.
- [284] N.E. Leadbeater, M. Macro, J. Org. Chem. 68 (2003) 888.
- [285] R.K. Arvela, N.E. Leadbeater, M.S. Sangi, V.A. Williams, P. Granados, R.D. Singer, J. Org. Chem. 70 (2005) 161.
- [286] R.K. Arvela, N.E. Leadbeater, T.L. Mack, C.M. Kormos, Tetrahedron Lett. 47 (2006) 217.
- [287] C. Li, Angew. Chem. Int. Ed. 42 (2003) 4856.
- [288] C. Nájera, J. Gil-Molto, S. Karlström, Adv. Synth. Catal. 346 (2004) 1798.
- [289] C. Chen, Y. Liu, S. Peng, S. Liu, Tetrahedron Lett. 46 (2005) 521.
- [290] C. Baleizao, A. Corma, H. Garcia, A. Leyva, Chem. Commun. (2003) 606.
- [291] C. Baleizao, A. Corma, H. Garcia, A. Leyva, J. Org. Chem. 69 (2004) 439.
- [292] J.-W. Byun, Y.-S. Lee, Tetrahedron Lett. 45 (2004) 1837.
- [293] J.-H. Kim, J.-W. Kim, M. Shokouhimehr, Y.-S. Lee, J. Org. Chem. 70 (2005) 6714.
- [294] Q. Yang, S. Ma, J. Li, F. Xiao, H. Xiong, Chem. Commun. (2006) 2495.
- [295] Y. Na, S. Park, S.B. Han, H. Han, S. Ko, S. Chang, J. Am. Chem. Soc. 126 (2004) 250.
- [296] F. Hapiot, J. Lyskawa, H. Bricout, S. Tilloy, E. Monflier, Adv. Synth. Catal. 346 (2004) 83.
- [297] Y.M.A. Yamada, K. Takeda, H. Takahashi, S. Ikegami, J. Org. Chem. 68 (2003) 7733.
- [298] M. Lee, C.-J. Jang, J.-H. Ryu, J. Am. Chem. Soc. 126 (2004) 8082.
- [299] C.C. Tzschucke, W. Bannwarth, Helvetica Chim. Acta 87 (2004) 2882.
- [300] C.C. Tzschucke, V. Andrushko, W. Bannwarth, Eur. J. Org. Chem. (2005) 5248.
- [301] P. Appukkuttan, A.B. Orts, R.P. Chandran, J.L. Goeman, J. Van der Eycken, W. Dehaen, E. Van der Eycken, Eur. J. Org. Chem. (2004) 3277.
- [302] W. Zhang, C.H.-T. Chen, Y. Lu, T. Nagashima, Org. Lett. 6 (2004) 1473.
- [303] N. Jiang, A.J. Ragauskas, Tetrahedron Lett. 47 (2006) 197.
- [304] G. Cravotto, G. Palmisano, S. Tollari, G.M. Nano, A. Penoni, Ultrasonics Sonochem. 12 (2005) 91.
- [305] V. Poláčková, M. Hut'ka, Š. Toma, Ultrasonics Sonochem. 12 (2005) 99.
- [306] P. He, S.J. Haswell, P.D.I. Fletcher, Appl. Catal. A: Gen. 274 (2004) 111.
- [307] C. Basheer, F. Shahitha, J. Hussain, H.K. Lee, S. Valiyaveetil, Tetrahedron Lett. 45 (2004) 7297.
- [308] F. McLachlan, C.J. Mathews, P.J. Smith, T. Welton, Organometallics 22 (2003) 5350.
- [309] J. Mnulty, A. Capretta, J. Wilson, J. Dyck, G. Adjabeng, A. Robertson, Chem. Commun. (2002) 1986.
- [310] G. Zou, Z.Y. Wang, J. Zhu, J. Tang, M.Y. He, J. Mol. Catal. A: Chem. 206 (2003) 193.
- [311] D. Zhao, Z. Fei, T.J. Geldbach, R. Scopelliti, P.J. Dyson, J. Am. Chem. Soc. 126 (2004) 15876.
- [312] C.J. Mathews, P.J. Smith, T. Welton, J. Mol. Catal. A: Chem. 214 (2004) 27.
- [313] C.-H. Yang, C.-C. Tai, Y.-T. Huang, I.-W. Sun, Tetrahedron 61 (2005) 4857.

- [314] J.-C. Xiao, J.M. Shreeve, *J. Org. Chem.* 70 (2005) 3072.
- [315] C. Rocaboy, J.A. Gladysz, *Tetrahedron* 58 (2002) 4007.
- [316] C.C. Tzschucke, C. Markert, H. Glatz, W. Bannwarth, *Angew. Chem. Int. Ed.* 41 (2002) 4500.
- [317] C. Chiappe, G. Imperato, E. Napolitano, D. Pieraccini, *Green Chem.* 6 (2004) 33.
- [318] S. Bhattacharya, S. Sengupta, *Tetrahedron Lett.* 45 (2004) 8733.
- [319] E. Genin, R. Amengual, V. Michelet, M. Savignac, A. Jutand, L. Neuville, J.-P. Genêt, *Adv. Synth. Catal.* 346 (2004) 1733.
- [320] J. Gil-Moltó, C. Nájera, *Eur. J. Org. Chem.* (2005) 4073.
- [321] B. Liang, M. Dai, J. Chen, Z. Yang, *J. Org. Chem.* 70 (2005) 391.
- [322] B. Liang, M. Huang, Z. You, Z. Xiong, K. Lu, R. Faithi, J. Chen, Z. Yang, *J. Org. Chem.* 70 (2005) 6097.
- [323] Z. Novák, A. Szabó, J. Répási, A. Kotschy, *J. Org. Chem.* 68 (2003) 3327.
- [324] M. Gruber, S. Chouzier, K. Kohler, L. Djakovitch, *Appl. Catal. A: Gen.* 265 (2004) 161.
- [325] V.R. Batchu, V. Subramanian, K. Parasuraman, N.K. Swamy, S. Kumar, M. Pal, *Tetrahedron* 61 (2005) 9869.
- [326] L. Djakovitch, P. Rollet, *Tetrahedron Lett.* 45 (2004) 1367.
- [327] N.E. Leadbeater, M. Macro, B.J. Tominack, *Org. Lett.* 5 (2003) 3919.
- [328] P. Appukkuttan, W. Dehaen, E. Van der Eycken, *Eur. J. Org. Chem.* (2003) 4713.
- [329] S.B. Park, H. Alper, *Chem. Commun.* (2004) 1306.
- [330] A.R. Gholap, K. Venkatesan, R. Pasricha, T. Daniel, R.J. Lahoti, K.V. Srinivasan, *J. Org. Chem.* 70 (2005) 4869.
- [331] D. Sinou, C. Rabeyrin, C. Nguéfacq, *Adv. Synth. Catal.* 345 (2003) 357.
- [332] F.-X. Felpin, Y. Landais, *J. Org. Chem.* 70 (2005) 6441.
- [333] H. Kinoshita, H. Shinokubo, K. Oshima, *Angew. Chem. Int. Ed.* 44 (2005) 2397.
- [334] Y. Uozumi, H. Tanaka, K. Shibatomi, *Org. Lett.* 6 (2004) 281.
- [335] K. Manabe, S. Kobayashi, *Org. Lett.* 5 (2003) 3241.
- [336] N.T. Patil, Y. Yamamoto, *Tetrahedron Lett.* 45 (2004) 3101.
- [337] H. Kinoshita, H. Shinokubo, K. Oshima, *Org. Lett.* 6 (2004) 4085.
- [338] S.-C. Yang, Y.-C. Hsu, K.-H. Gan, *Tetrahedron* 62 (2006) 3949.
- [339] C. Chevrin, J.L. Bras, F. Héning, J. Muzart, *Tetrahedron Lett.* 44 (2003) 8099.
- [340] C. Chevrin, J.L. Bras, F. Héning, J. Muzart, *Organometallics* 23 (2004) 4796.
- [341] M. Liao, X. Duan, Y. Liang, *Tetrahedron Lett.* 46 (2005) 3469.
- [342] C. Hubert, J.-L. Renaud, B. Demerseman, C. Fischmeister, C. Bruneau, *J. Mol. Catal. A: Gen.* 237 (2005) 161.
- [343] J. Bayardon, D. Sinou, *Tetrahedron Lett.* 44 (2003) 1449.
- [344] J. Bayardon, M. Cavazzini, D. Maillard, G. Pozzi, S. Quici, D. Sinou, *Tetrahedron: Asymm.* 14 (2003) 2215.
- [345] J. Bayardon, D. Sinou, *Tetrahedron: Asymm.* 16 (2005) 2965.
- [346] (a) P. Schwab, R.H. Grubbs, J.W. Ziller, *J. Am. Chem. Soc.* 118 (1996) 100;
(b) M. Scholl, S. Ding, C.W. Lee, R.H. Grubbs, *Org. Lett.* 1 (1999) 953.
- [347] (a) J.S. Kingsbury, J.P.A. Harrity, P.J. Bonitatebus, A.H. Hoveyda, *J. Am. Chem. Soc.* 121 (1999) 791;
(b) S.B. Carber, J.S. Kingsbury, B.L. Gray, A.H. Hoveyda, *J. Am. Chem. Soc.* 122 (2000) 8168.
- [348] (a) D.M. Lynn, B. Mohr, L.M. Henling, M.W. Day, R.H. Grubbs, *J. Am. Chem. Soc.* 122 (2000) 6601;
(b) S.J. Connon, M. Rivard, M. Zaja, S. Blechert, *Adv. Synth. Catal.* 345 (2003) 572.
- [349] J.P. Gallivan, J.P. Jordan, R.H. Grubbs, *Tetrahedron Lett.* 46 (2005) 2577.
- [350] S.H. Hong, R.H. Grubbs, *J. Am. Chem. Soc.* 128 (2006) 3508.
- [351] K. Breitenkamp, T. Emrick, *J. Polym. Sci. Part A: Polym. Chem.* 43 (2005) 5715.
- [352] D. Quémener, V. Héroguez, Y. Gnanou, *Macromolecules* 38 (2005) 7977.
- [353] D. Quémener, V. Héroguez, Y. Gnanou, *J. Polym. Sci. Part A: Polym. Chem.* 44 (2006) 2784.
- [354] M.T. Zarka, O. Nuyken, R. Weberskirch, *Macromol. Rapid Commun.* 25 (2004) 858.
- [355] D.B.G. Williams, M. Ajam, A. Ranwell, *Organometallics* 25 (2006) 3088.
- [356] N. Audic, H. Clavier, M. Mauduit, J.-C. Guillemin, *J. Am. Chem. Soc.* 125 (2003) 9248.
- [357] H. Clavier, N. Audic, M. Mauduit, J.-C. Guillemin, *Chem. Commun.* (2004) 2282.
- [358] H. Clavier, N. Audic, J.-C. Guillemin, M. Mauduit, *J. Organomet. Chem.* 690 (2005) 3585.
- [359] Q. Yao, Y. Zhang, *Angew. Chem. Int. Ed.* 42 (2003) 3395.
- [360] Q. Yao, M. Sheets, *J. Organomet. Chem.* 690 (2005) 3577.
- [361] X. Hu, M.T. Blanda, S.R. Venumbaka, P.E. Cassidy, *Polym. Adv. Technol.* 16 (2005) 146.
- [362] F. Michalek, D. Mäde, J. Ruhe, W. Bannwarth, *Eur. J. Org. Chem.* (2006) 577.
- [363] Q. Yao, Y. Zhang, *J. Am. Chem. Soc.* 126 (2004) 74.
- [364] M. Matsugi, D.P. Curran, *J. Org. Chem.* 70 (2005) 1636.
- [365] R. Corrêa da Costa, J.A. Gladysz, *Chem. Commun.* (2006) 2619.
- [366] B.S. Lane, K. Burgess, *Chem. Rev.* 103 (2003) 2457.
- [367] G. Grigoropoulou, J.H. Clark, J.A. Elings, *Green Chem.* 5 (2003) 1.
- [368] K. Kamata, K. Yonehara, Y. Sumida, K. Yamaguchi, S. Hikichi, N. Mizuno, *Science* 300 (2003) 964.
- [369] K. Kamata, K. Yamaguchi, S. Hikichi, N. Mizuno, *Adv. Synth. Catal.* 345 (2003) 1193.
- [370] K. Kamata, K. Yamaguchi, N. Mizuno, *Chem. -Eur. J.* 10 (2004) 4728.
- [371] A. Masuyama, K. Fukuoka, N. Katsuyama, M. Nojima, *Langmuir* 20 (2004) 82.
- [372] A. Masuyama, T. Yamaguchi, M. Abe, M. Nojima, *Tetrahedron Lett.* 46 (2005) 213.
- [373] V.R. Choudhary, N.S. Patil, N.K. Chaudhai, S.K. Bhargava, *Catal. Commun.* 5 (2004) 205.
- [374] S. Casuscelli, E. Herrero, M. Crivello, C. Pérez, M.G. Egusquiza, C.I. Cabello, I.L. Botto, *Catal. Today* 107–108 (2005) 230.
- [375] Z. Bourhani, A.V. Malkov, *Chem. Commun.* (2005) 4592.
- [376] W. Zhuang, M. Marigo, K.A. Jørgensen, *Org. Biomol. Chem.* 3 (2005) 3883.
- [377] B. Wang, Y. Kang, L. Yang, J. Suo, *J. Mol. Catal. A: Chem.* 203 (2003) 29.
- [378] O. Bortolini, S. Campestrini, V. Conte, G. Fanin, M. Fogagnolo, S. Maietti, *Eur. J. Org. Chem.* (2003) 4804.
- [379] J. Sun, S. Fujita, B.M. Bhanage, M. Arai, *Catal. Commun.* 5 (2004) 83.
- [380] F.E. Kühn, J. Zhao, M. Abrantes, W. Sun, C.A.M. Afonso, L.C. Branco, I.S. Goncalves, M. Pillinger, C.C. Romão, *Tetrahedron Lett.* 46 (2005) 47.
- [381] M.C.-Y. Tang, K.-Y. Wong, T.H. Chan, *Chem. Commun.* (2005) 1345.
- [382] K. Smith, S. Liu, G.A. El-Hiti, *Catal. Lett.* 98 (2004) 95.
- [383] K. Yamaguchi, C. Yoshida, S. Uchida, N. Mizuno, *J. Am. Chem. Soc.* 127 (2005) 530.
- [384] S. Campestrini, A. Donoli, U. Tonellato, *Lett. Org. Chem.* 1 (2004) 125.
- [385] G. Maayan, R.H. Fish, R. Neumann, *Org. Lett.* 5 (2003) 3547.
- [386] For a review on metal mediated oxidation, see: W.J. Mijis, C.R.H. de Jonge (Eds.), *Organic Synthesis by Oxidation with Metal Compounds*, Plenum, New York, 1986.
- [387] (a) K.B. Sharpless, T.R. Verhoeven, *Aldrichim. Acta* 12 (1979) 63;
(b) J. Muzart, *Tetrahedron Lett.* 27 (1986) 3139;
(c) J. Muzart, A. Nait-Ajjou, *J. Mol. Catal.* 66 (1991) 155.
- [388] (a) For recent review, see: R.A. Sheldon, I.W.C.E. Arends, A. Dijkstra, *Catal. Today* 57 (2000) 157;
(b) R.A. Sheldon, I.W.C.E. Arends, G.-J. ten Brink, A. Dijkstra, *Acc. Chem. Res.* 35 (2002) 774;
(c) J. Muzart, *Tetrahedron* 59 (2003) 5789;
(d) S.S. Stahl, *Angew. Chem. Int. Ed.* 43 (2004) 3400.
- [389] G.-J. ten Brink, I.W.C.E. Arends, R.A. Sheldon, *Science* 287 (2000) 1636.
- [390] G.-J. ten Brink, I.W.C.E. Arends, R.A. Sheldon, *Adv. Synth. Catal.* 344 (2002) 355.
- [391] G.-J. ten Brink, I.W.C.E. Arends, M. Hoogenraad, G. Verspui, R.A. Sheldon, *Adv. Synth. Catal.* 345 (2003) 497.
- [392] G.-J. ten Brink, I.W.C.E. Arends, M. Hoogenraad, G. Verspui, R.A. Sheldon, *Adv. Synth. Catal.* 345 (2003) 1341.
- [393] I.W.C.E. Arends, G.-J. ten Brink, R.A. Sheldon, *J. Mol. Catal. A: Chem.* 251 (2006) 246.
- [394] B.P. Buffin, J.P. Clarkson, N.L. Belitz, A. Kundu, *J. Mol. Catal. A: Chem.* 225 (2005) 111.

- [395] Y. Uozumi, R. Nakao, *Angew. Chem. Int. Ed.* 42 (2003) 194.
- [396] (a) B.A. Steinhoff, I.A. Guzei, S.S. Stahl, *J. Am. Chem. Soc.* 126 (2004) 11268;
(b) M.J. Schultz, R.S. Adler, W. Zierkiewicz, T. Privalov, M.S. Sigman, *J. Am. Chem. Soc.* 127 (2005) 8499.
- [397] C.N. Kato, A. Shinohara, N. Moriya, K. Nomiya, *Catal. Commun.* 7 (2006) 413.
- [398] K. Kervinen, H. Korpi, J.G. Mesu, F. Soulimani, T. Repo, B. Rieger, M. Leskelä, B.M. Weckhusen, *Eur. J. Inorg. Chem.* (2005) 2591.
- [399] A. Biffs, L. Minati, *J. Catal.* 236 (2006) 405.
- [400] H. Tusnoyama, H. Sakurai, Y. Negishi, T. Tsukuda, *J. Am. Chem. Soc.* 127 (2005) 9374.
- [401] R. Neumann, M. Gara, *J. Am. Chem. Soc.* 117 (1995) 5066.
- [402] D. Sloboda-Rozner, P.L. Alsters, R. Neumann, *J. Am. Chem. Soc.* 125 (2003) 5280.
- [403] D. Sloboda-Rozner, P. Witte, P.L. Alsters, R. Neumann, *Adv. Synth. Catal.* 346 (2004) 339.
- [404] J. Wang, L. Yan, G. Li, X. Wang, Y. Ding, J. Suo, *Tetrahedron Lett.* 46 (2005) 7023.
- [405] C.M. Thomas, C. Letondor, N. Humbert, T.R. Ward, *J. Organomet. Chem.* 690 (2005) 4488.
- [406] A. Köckritz, M. Sebek, A. Dittmar, J. Radnik, A. Brückner, U. Bentrup, M.-M. Pohl, H. Hugl, W. Mägerlein, *J. Mol. Catal. A: Chem.* 246 (2006) 85.
- [407] G. Ferguson, A.N. Ajjou, *Tetrahedron Lett.* 44 (2003) 9139.
- [408] J. Boudreau, M. Doucette, A.N. Ajjou, *Tetrahedron Lett.* 47 (2006) 1695.
- [409] R. Ciriminna, M. Pagliaro, *Adv. Synth. Catal.* 345 (2003) 383.
- [410] S. Montanari, M. Roumani, L. Heux, M.R. Vignon, *Macromolecules* 38 (2005) 1665.
- [411] W. Qian, E. Jin, W. Bao, Y. Zhang, *Tetrahedron* 62 (2006) 556.
- [412] Z. Liu, Z. Chen, Q. Zheng, *Org. Lett.* 5 (2003) 3321.
- [413] J.S. Yadav, B.V.S. Reddy, A.K. Basak, A.V. Narsaiah, *Tetrahedron* 60 (2004) 2131.
- [414] W. Qian, E. Jin, W. Bao, Y. Zhang, *Angew. Chem. Int. Ed.* 44 (2005) 952.
- [415] B.S. Chhikara, R. Chandra, V. Tandon, *J. Catal.* 230 (2005) 436.
- [416] N. Jiang, A.J. Ragauskas, *Tetrahedron Lett.* 46 (2005) 3323.
- [417] N. Jiang, A.J. Ragauskas, *Org. Lett.* 7 (2005) 3689.
- [418] G. Zhao, T. Jiang, W. Wu, B. Han, Z. Liu, H. Gao, *J. Phys. Chem. B* 108 (2004) 13052.
- [419] M. Caravati, J.-D. Grunwaldt, A. Baiker, *Catal. Today* 91–92 (2004) 1.
- [420] M. Caravati, J.-D. Grunwaldt, A. Baiker, *Phys. Chem. Chem. Phys.* 7 (2005) 278.
- [421] M. Caravati, J.-D. Grunwaldt, A. Baiker, *Appl. Catal. A: Gen.* 298 (2006) 50.
- [422] J.-D. Grunwaldt, M. Caravati, A. Baiker, *J. Phys. Chem. B* 110 (2006) 9916.
- [423] M. Caravati, D.M. Meier, J.-D. Grunwaldt, A. Baiker, *J. Catal.* 240 (2006) 126.
- [424] M. Burgener, T. Tyszewski, D. Ferri, T. Mallat, A. Baiker, *Appl. Catal. A: Gen.* 299 (2006) 66.
- [425] M. Burgener, T. Mallat, A. Baiker, *J. Mol. Catal. A: Chem.* 225 (2005) 21.
- [426] S.C. Tsang, J. Zhu, A.M. Steele, P. Meric, *J. Catal.* 226 (2004) 435.
- [427] M.E. González-Núñez, R. Mello, A. Olmos, R. Acerete, G. Asensio, *J. Org. Chem.* 71 (2006) 1039.
- [428] R. Ciriminna, S. Campestrini, M. Pagliaro, *Org. Biomol. Chem.* 4 (2006) 2637.
- [429] S. Campestrini, M. Carraro, R. Ciriminna, M. Pagliaro, U. Tonellato, *Adv. Synth. Catal.* 347 (2005) 825.
- [430] M. Contel, C. Izuel, M. Laguna, P.R. Villuenadas, P.J. Alonso, R.H. Fish, *Chem. -Eur. J.* 9 (2003) 4168.
- [431] M. Contel, P.R. Villuenadas, J. Fernández-Gallardo, P.J. Alonso, J.-M. Vincent, R.H. Fish, *Inorg. Chem.* 44 (2005) 9771.
- [432] J.J. Maul, P.J. Ostrowski, G.A. Ublacker, B. Linclau, D.P. Curran, in: P. Knochel (Ed.), *Modern Solvents in Organic Synthesis, Topics in Current Chemistry*, vol. 206, Springer-Verlag, Berlin, 1999.
- [433] N. Wang, R. Liu, J. Chen, X. Liang, *Chem. Commun.* (2005) 5322.
- [434] (a) M. Butters, D. Catterick, A. Craig, A. Curzons, D. Dale, A. Gillmore, S.P. Green, I. Marziano, J.-P. Sherlock, W. White, *Chem. Rev.* 106 (2006) 3002;
(b) J.S. Carey, D. Laffan, C. Thomson, M.T. Williams, *Org. Biomol. Chem.* 4 (2006) 2337.