Oxidative carbonylation of amine using water-soluble palladium catalysts in biphasic media

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ABSTRACT

Application of water-soluble palladium catalysts for oxidative carbonylation of aniline to N,N′ diphenyl urea (DPU) has been reported. The water-soluble palladium catalysts prepared from sulfonated N-containing ligands were found to be highly stable under reaction conditions and easily recyclable due to insoluble urea product in the reaction medium. This is in contrast to the sulfonated phosphine ligands, which are vulnerable to oxidation under reaction conditions, showing poor activity and stability. Commercially available as well as laboratory synthesized ligands were used for preparing water-soluble palladium catalysts, for oxidative carbonylation of aniline. The best activity was obtained for Pd complex with disodium 2,2′-bipyridine-4,4′-disulfonate (Bipy-DS) ligand. Under optimized conditions Pd(BipyDS)Pd(OAc)$_2$ catalyst gave TOF of $\sim$210 h^{-1} with aniline conversion of $\sim$97% with $\sim$91% selectivity for N,N′-diphenyl urea. It was found that the catalyst was easily reusable up to five times, with negligible loss in the catalytic activity. The effect of reaction parameters was investigated and a plausible reaction mechanism has been proposed.

1. Introduction

Synthesis of substituted ureas by oxidative carbonylation of amines is an attractive alternative to the conventional phosgenation route; however, it has limitations due to processing difficulties such as poor solubility of inorganic halide salt promoters (e.g. NaI, KI, etc.) in the organic solvents, inefficient catalyst recovery from reaction mixture and contamination of product by halide promoter used. Often polar solvents such as dimethyl formamide, N-methyl pyrrolidone and dimethyl sulfoxides are used either as solvents or co-solvents to enhance the activity of the catalysts [1]. However, the leaching of active components from supported noble metal catalysts (e.g. Pd/C) in highly polar and corrosive halide containing medium further complicates the issue of recovery and recycle of the catalyst (and of product urea). In many cases, water (product of reaction) has become detrimental to the catalytic system and water quenching agents such as molecular sieves, orthoformates, acetals and enol ethers have been employed to improve the yields [2]. Homogeneous Pd [3–5], Rh [6,7] and Ru [8] metal

complex catalysts in combination with iodide promoters have also been shown to be effective for the reaction. McCusker et al. [9] have shown that oxidative carbonylation of amines to urea derivatives can be efficiently carried out using W(CO)$_6$ catalyst in a water–dichloromethane biphasic media. They have shown exceptionally efficient catalyst–product separation as well as excellent product purity. However, iodine promoter was required in substrate to iodide ratio of two and was not recyclable. In order to develop a practically useful catalyst system, molecular oxygen needs to be employed in place of iodine as a re-oxidant. In this connection, several supported metal catalysts, mostly consisting of palladium, have been investigated in detail [4,6,10]. However, the major problem in both homogeneous and heterogeneous catalysis is the sparing solubility of the aromatic urea even in highly polar solvents. Catalyst separation methods like sieving have been used in such cases, which may lead to loss of expensive catalyst [11]. Shi et al. have developed a homogeneous catalyst system consisting of a palladium complex and ionic liquid [5]. The reaction occurs in homogeneous phase and at the end of the reaction, water is added creating biphasic conditions wherein the catalyst components separate into the aqueous phase, while the product (and unconverted amine byproducts, etc.) remains in the organic phase. Water is then distilled off to recover the catalytic phase for recycle, while purified product can be obtained by separation.

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In the present work we demonstrated that aqueous–organic biphasic catalytic system involving a water-soluble catalyst can be of a great advantage in terms of catalyst and product separation and at the same time easy recycling of homogeneous catalyst.

2. Experimental

2.1. Synthesis of water-soluble ligands

Isoquinoline-5-sulfonic acid sodium salt (IQS-Na) was synthesized by simple neutralization of isoquinoline-5-sulfonic acid (IQS) using NaOH. To an aqueous solution of IQS (1.0 g; 4.779 mmol in 5 g deionized water), a cold aqueous solution of sodium hydroxide (0.172 g; 4.779 mmol, 20% w/v) was added drop wise and kept under continuous stirring for 2 h at room temperature under inert atmosphere. This solution was concentrated on rota-evaporator at 60 °C, resulting in a white solid which was washed with 90% methanol several times and vacuum dried. The water-soluble ligand IQS-Na was analyzed by elemental analysis. Triphenylphosphine trisulfonate sodium salt (TPPTS) was synthesized according to the literature procedure by sulfonation of triphenylphosphine [12]. The solid TPPTS obtained was recrystallized from ethanol, weighed and stored under argon atmosphere. The yield was found to be 80–85%. TPPTS was characterized by ^{31}P NMR analysis (singlet at $\delta = -5.15$ (TPPTS) and $\delta = 35.22$ (OTPPTS)) which is consistent with that reported in the literature [12], showing approximately 95% TPPTS and 5% OTPPTS formation. For the synthesis of water-soluble Pd complex, TPPTS was used as synthesized without further purification. Sulfonated N-containing ligands were synthesized according to literature procedure involving five steps [13]. These ligands were characterized by IR, NMR and elemental analysis.

2.2. Synthesis of Pd(OAc)$_2$(Bipy)

A solution of palladium acetate (100 mg, 0.4455 mmol) was prepared in 10 ml chloroform, and a solution of 2,2′-bipyridine (84 mg, 0.5378 mmol; 1.2 equivalent of Pd) in 5 ml chloroform was added to it dropwise, the complex started precipitating out gradually, and the solution was further stirred at room temperature for 1 h. The solvent was removed by filtration, and the yellow solid obtained was dried using vacuum at room temperature. A yellow crystalline solid of Pd(OAc)$_2$(Bipy) which was obtained was characterized by elemental analysis.

2.3. Synthesis of water soluble palladium complexes

Water-soluble palladium complexes of sulfonated N-containing ligands were prepared by stirring the ligand and palladium precursor overnight at room temperature. In typical experiment water soluble ligand BipyDS (192.6 mg, 0.5345 mmol; 1.2 equivalent of Pd) was dissolved in 5 ml degassed distilled water in a round-bottomed flask with the help of a magnetic needle. The solution appeared faint pink in color. To this solution 100 mg (0.4454 mmol) of palladium acetate was added under stirring. The solution was kept under vigorous stirring at room temperature for 12 h. At the end of 12 h, a clear, homogeneous, brownish solution was obtained. This solution was diluted to 10 ml using distilled water. For the synthesis of water-soluble complexes of rhodium and ruthenium similar procedure shown above was followed.

2.4. Oxidative carbonylation of aniline, isolation and characterization of products

The reactions were carried out in a 600 ml Parr Hastelloy-C-276 autoclave; provided with gas inlet, gas outlet, a safety rupture disc (gold faced, 140 bar), pressure, digital temperature, control
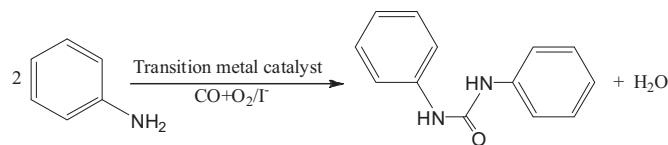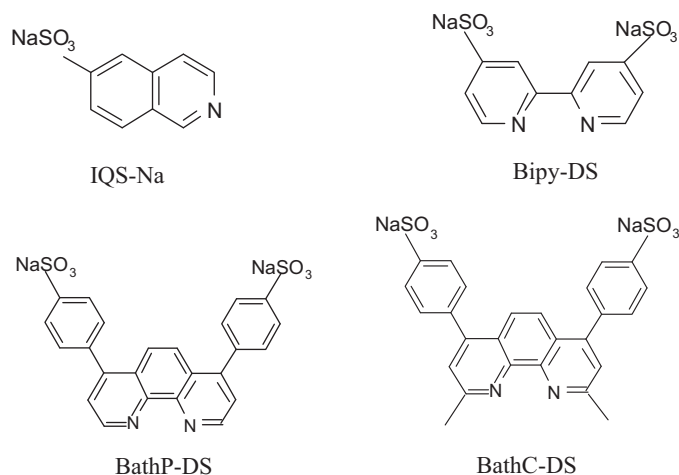

Scheme 1. Oxidative carbonylation of aniline to N,N′ diphenyl urea.

($\pm$1 K) and a magnetically driven stirrer having variable agitation speed adjustment and indicator. In a typical experiment (these conditions are henceforth referred to as standard conditions), weighed amounts of aniline (74 mmol), toluene (50 ml), water (10 ml), sodium iodide (0.90 mmol) and the water-soluble catalyst Pd(OAc)$_2$BipyDS (0.078 mmol), were charged and the autoclave was sealed. The autoclave was purged once with nitrogen and thrice with carbon monoxide; and then pressurized with the carbon monoxide under constant stirring. Oxygen was then pressurized into the autoclave, so as to make the ratio of carbon monoxide to oxygen 13:1. Pressure at 423 K reached up-to 68.9 bar. It was observed that reproducibility of standard reaction (measured as TOF values) was sensitive to slight variations in the amount of oxygen introduced at the initial stage (a typical average deviation in TOF value of a standard reaction was 4.8). The heating was started, and an agitation speed of 16.66 Hz (1000 R.P.M.) was set as the temperature reached 423 K. The progress of the reaction was monitored by observing the pressure drop in the autoclave and by feeding a 2:1 mixture of CO and O$_2$ from a reservoir vessel in order to keep the reactor pressure constant at 68–69 bar. (Caution! The reaction conditions employed in the work were safe from point of view of explosion limits; however, special precautions should be taken when reactions of CO and O$_2$ mixture under high-pressure are performed. Proper safety precautions against explosion hazards such as performing the experiments in well ventilated and isolated cubicle having equipment control operable from out side were employed during this work.) The reaction was carried out for 2 h time duration and at the end of which, the contents were cooled to room temperature. Gas phase was analyzed for CO, O$_2$ and CO$_2$ using ORSAT apparatus before venting off in a hood under continuous vacuum, and then the autoclave was opened. The solid urea (DPU) formed in the reaction was filtered off, washed with cold petroleum ether, dried and weighed. The two phases in the filtrate were separated using a separating funnel. The organic phase was then analyzed by gas chromatography for estimating the unreacted aniline. The organic phase was concentrated using rotary evaporator at 323 K to remove the solvent. The solid and the concentrate from organic layer of the filtrate were then dissolved in weighed quantity of dimethyl formamide, and the solution was analyzed by HPLC to determine the amount of substituted urea formed in the reaction. Crystals of urea recovered at the end of the reaction were analyzed by IR, ^{1}H and ^{13}C NMR and elemental analysis (see supplementary materials for details). For recycle experiments, water soluble catalyst was recycled simply by recycling the aqueous phase containing catalyst. Fresh lot of 0.68 mmol of NaI was also added during each recycle to compensate for NaI lost in organic phase.

3. Results and discussion

Few preliminary reactions were carried out to establish catalytic activity (based on turnover frequency, TOF (h^{-1})) of conventional Pd/C–NaI catalyst system for oxidative carbonylation of aniline in dimethyl formamide as the solvent [1]. As expected, excellent aniline conversion ($\sim$99%) and yield ($\sim$97%) of DPU with TOF of 37 h^{-1} were observed according to stoichiometry shown in Scheme 1.

Scheme 2. Water-soluble sulfonated ligands screened for biphasic oxidative carbonylation of aniline.

3.1. Catalyst screening

The water-soluble palladium, rhodium and ruthenium salts were compared for their catalytic activity for oxidative carbonylation of aniline under standard aqueous-biphasic reaction conditions and in the presence of excess water-soluble BipyDS ligand. Under the experimental conditions, the corresponding metal complexes with BipyDS ligand are presumably formed which are believed to be the active catalysts. The results obtained are shown in Table 1. The water-soluble palladium complex formed from palladium acetate and BipyDS ligand was found to be the most active with TOF of 221 h^{-1} and the yield of DPU 88.6% (see entry 1). Therefore, it was decided to screen palladium complexes synthesized from palladium acetate and other water-soluble ligands for oxidative carbonylation of aniline as the substrate.

3.2. Screening of water soluble N-containing ligands

It is known that water soluble sulfonated phosphine ligands such as TPPTS are prone to oxidation, but their *N*-analogues are resistant to oxidation in the presence of oxygen or air [14]. Therefore, *N*-containing heterocyclic ligands along with TPPTS were chosen for the screening purpose in the present study. Commercially available as well as laboratory synthesized ligands from published literature were used for preparing water-soluble palladium catalysts (from Pd(OAc)$_2$ precursor). These were evaluated for oxidative carbonylation of aniline, using a toluene–water biphasic medium and sodium iodide as a halide promoter. The *N*-containing ligands screened were: isoquinoline sulfonic acid sodium salt (IQS-Na) as a monodentate ligand, disodium 2,2′-bipyridine disulfonate (Bipy-DS), bathophenanthroline disulfonic acid disodium salt (BathP-DS) and bathocuproine disulfonic acid disodium salt (BathC-DS) as bidentate ligands (see Scheme 2). The effect of ligands on conversion of aniline was studied under standard reaction conditions and results are presented in Table 2. Catalysts prepared from bidentate *N*-containing ligands were more active (TOF in the range of 513–543 h^{-1}, see Table 2, entries 2–4 respectively) compared to those with monodentate *N*-containing ligand (entry 1). The selectivity towards DPU however remained high in all the cases. For bidentate ligands, the aniline conversion levels achieved were more or less the same and no significant effect of increasing steric hindrance of bidentate *N*-containing ligand was observed on the reaction (see entries 2–4); this is contrast with the observations made by Ishii et al. in the oxidative carbonylation of phenol [15]. Further optimization of biphasic system was therefore carried out using Bipy-DS ligand. No palladium precipitation was observed under these conditions (entry 2), and the product *N,N′*-diphenyl urea was found to be precipitated in the reaction medium, and could be easily separated by filtration. The aqueous layer consisting of the water-soluble palladium complex could be conveniently separated by phase separation.

3.3. Development of biphasic system

For the development of a biphasic system, the activity of homogeneous catalyst Pd(OAc)$_2$(Bipy) was considered as a benchmark, against which the present biphasic system was compared. The activity of Pd(OAc)$_2$(Bipy) catalyst in toluene (see Table 3, entry 1, TOF 210 h^{-1}) was significantly higher comparable to Pd–NaI–DMF system (TOF 37 h^{-1}) [1]. This was unlike 5% Pd/C–NaI–toluene system, wherein even poorer conversions to urea were realized in toluene as a solvent (TOF 7 h^{-1}) [1]. Pd(OAc)$_2$(Bipy)–toluene system under 5:1, toluene:water biphasic condition gave tarry material with lowering the selectivity of DPU (entry 2) and with water as solvent only ∼65% of DPU selectivity with TOF of 86 h^{-1} was observed (entry 3). Several water-soluble Pd complexes were evaluated under biphasic conditions, the palladium complex prepared from water-soluble sulfonated phosphine ligand e.g. TPPTS gave very poor activity for urea formation under biphasic conditions due to metal precipitation (TOF 56 h^{-1}, entry 8). While, it was also observed that in water medium the water-soluble complex Pd(OAc)(BipyDS) was less efficient compared to its organic analogue, i.e., Pd(OAc)$_2$(Bipy) (see Table 3, entries 1 and 6). The lower activity of Pd(OAc)$_2$(Bipy) catalyst in water (entry 3) medium could be due to poor solubility of CO and O$_2$ in the aqueous catalytic phase. The activity of water-soluble catalyst Pd(OAc)(BipyDS) could be improved by performing the reaction in a biphasic toluene–water phase (see entries 4 and 5). Under optimized biphasic conditions (toluene:water; 5:1), the activity of water soluble Pd(OAc)$_2$(BipyDS) complex catalyst was comparable to that of Pd(OAc)$_2$(Bipy) in the homogeneous phase with toluene as a solvent (entries 1 and 5) but significantly higher than the literature bench mark with supported Pd catalysts (TOF 37 h^{-1}). Thus, it has been observed that for the water-soluble catalysts, conversion and the selectivity depend on the ratio of the aqueous and organic phase hold-ups (entries 4, 5 and 6). It can be seen that most of the reaction takes place at the L–L interface as increase in organic phase increase the conversion of aniline (entries 6, 5 and 4). This result is justified by the fact that the reaction rates depend largely on the mass transfer of the substrate from organic phase into the aqueous phase, which in turn is based on the L–L interface value of organic phase and water, as well as concentration gradient of aniline in two phases. It may be noted that, in water alone as a solvent catalyst system shows considerable activity (entry 6), indicating that second liquid phase (omega phase) e.g. aniline and quaternary ammonium salt as a combined organic phase might contribute to observed activity (this aspect is further discussed in Section 3.12 under mechanism). An experiment was carried out in the absence of iodide promoter, which resulted in no aniline conversion; confirming to the literature reports that oxidative carbonylation of amine essentially requires an iodide promoter [2,4] (entry 7).

3.4. Solvent screening

Several organic solvents were screened for the aqueous-biphasic reactions using the optimized solvent composition (organic to aqueous volume ratio of 5). The performance of organic–aqueous biphasic systems usually depends on solvent properties such as (a) polarity of the organic solvent, (b) solubility of the liquid phase substrate (aniline in this case) in organic phase,

Table 1
Results on catalytic performance of different precursors with water soluble Bipy-DS ligand.[a]

Sr. No.	Catalyst precursor[b]	Aniline conversion (%)	DPU (%)		TOF (h^{-1})
			Selectivity	Yield	
1	Pd(OAc)$_2$	97.2	95.6	88.6	221
2	RhCl$_3$·xH$_2$O	86.5	92.8	80.2	190
3	RuCl$_3$·xH$_2$O	77.1	90.5	69.8	166

[a] Aniline 74 mmol, catalyst precursor 0.078 mmol, Bipy-DS 0.156 mmol, water 10 ml, toluene 50 ml, NaI 0.90 mmol, T 423 K, pressure 68.9 bar, CO:O$_2$ 13:1, agitation 16.66 Hz, time 2 h.

[b] The precursors and the ligand were stirred at room temperature in deionized water overnight to make the water-soluble complex, which was charged in to the reaction.

Table 2
Results on effect of water-soluble (WS) ligands on catalytic performance using Pd(OAc)$_2$ precursor (time 0.5 h).

Sr. No.	WS-N-ligand (L/Pd ratio)	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
1	IQS-Na (2:4)	32.7	96.5	300
2	Bipy-DS (1:2)	58.7	97.5	543
3	BathP-DS (1:2)	59.1	94.8	531
4	BathC-DS (1:2)	55.9	96.7	513

Table 3
Screening of water-soluble Pd complexes (Pd; 0.078 mmol, time 2.0 h).

Sr. No.	Catalyst	Solvent composition (ratio, v/v)	Aniline conversion[a] (%)	DPU selectivity[b] (%)	TOF (h^{-1})
1	Pd(OAc)$_2$(Bipy)	Toluene	97.1	91.2	210
2	Pd(OAc)$_2$(Bipy)	Toluene + water (5:1)	78.3	77.1	143
3	Pd(OAc)$_2$(Bipy)	Water	56.3	64.5	86
4	Pd(OAc)$_2$(BipyDS)	Toluene + water (1:1)	81.7	89.7	174
5	Pd(OAc)$_2$(BipyDS)	Toluene + water (5:1)	94.5	95.9	215
6	Pd(OAc)$_2$(BipyDS)	Water	61.3	81.4	119
7[c]	Pd(OAc)$_2$(BipyDS)	Toluene + water (5:1)	0	0	0
8[d]	Pd(TPPTS)$_2$	Toluene + water (5:1)	30.0	78.1	56

[a] Determined by GC versus standards.
[b] Determined by HPLC versus standards.
[c] Reaction in absence of NaI.
[d] Pd precipitation was observed.

(c) solubility of gases as reactants in the organic phase, (d) miscibility or solubility of the organic solvent in water, and (e) solubility of products in the organic and aqueous phases. The results along with physical properties of solvents are presented in Table 4. The solubility and diffusivity of reactants depend on solvent properties such as polarity, dielectric constant and viscosity, which ultimately control the reaction rates. It was observed that the conversion of aniline was excellent (>85%) in all the cases except p-xylene, wherein lower TOF value (168 h^{-1}) was observed.

3.5. Screening of iodide promoters

Several iodide-containing compounds were also screened for their activity as promoters under biphasic conditions. The results are presented in Table 5. From the iodide-screening results, it was quite evident that iodide promoters having good solubility (>10% w/v solubility) in water showed excellent activity (HI, KI, NaI, TBAI, CsI, LiI, TOF ~ 200 h^{-1}). In case of iodine, for example, the lack of required concentration of iodide in aqueous phase due to sparing

Table 5
Screening of iodide promoters.

Iodide promoter	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
EtI	61.3	93.6	136
I$_2$	68.2	92.6	150
HI	83.1	95.6	188
KI	89.9	91.8	196
NaI	95.1	96.4	217
TBAI	96.2	95.3	217
CsI	95.8	94.1	214
LiI	96.8	93.6	215

TBAI = tetrabutyl ammonium iodide.

solubility in water (solubility of iodine in water is only 3.3 × 10^{-2} g per 100 g water at 25 °C) [16] results in a lower yield of DPU. Accordingly, ethyl iodide is sparingly soluble in water, and the conversion of aniline was much lower, although the selectivity to DPU was not affected in all cases (>90%). It was observed that all the alkali metal iodides as well as tetraethylammonium iodide were excel-

Table 4
Effect of solvents on diphenyl urea yield.

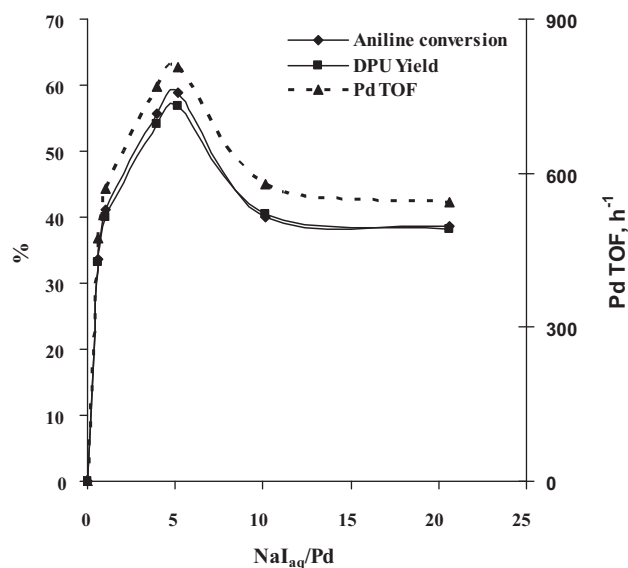| Solvent	Wm[a] (%)	Conversion (%)	DPU selectivity (%)	TOF (h^{-1})
Cyclohexane	0.01	89.5	96.0	204
Toluene	0.05	96.8	98.1	225
Diethylether	6.89	88.4	97.2	204
Benzene	0.18	87.0	96.3	199
Chlorobenzene	N.A.	93.4	96.0	213
Heptane	0.0003	93.0	93.1	205
p-Xylene	0.018	73.0	96.8	168

[a] Water miscibility (w/w).

Fig. 1. Effect of iodide loading (reaction time 0.33 h).

lent promoters for the reaction. These observations indicate that the catalytic reaction takes place at the interface phase, and not in the bulk liquid phase. NaI was used as the iodide promoter for further studies as it was convenient and cost effective.

3.6. Effect of sodium iodide promoter

Effect of NaI/Pd ratio was investigated and the results are shown in Fig. 1. The optimum NaI/Pd ratio for which the highest conversion of aniline and TOF were obtained, was found to be ~5 which is higher than that reported earlier by Gupte and Chaudhari [1]. The higher value of NaI/Pd ratio observed in the present study may be attributed to the partitioning of iodide in organic and aqueous phases, which decreases the effective concentration of iodide in the reaction phase and hence ultimately needs higher amount of NaI for optimum activity of the catalyst.

3.7. Effect of reaction parameters

Effects of temperature, aniline concentration and partial pressures of carbon monoxide and oxygen were investigated under biphasic conditions. Reactions were carried out using aniline as a substrate and $Pd(OAc)_2(BipyDS)$–NaI as the catalyst system with typically 30 min of reaction time. The effect of temperature on oxidative carbonylation of aniline was studied in the range of 373–443 K (see Table 6). The results show that the catalyst system is robust in the temperature range investigated. Catalyst activity was found to increase with increase in temperature. DPU selectivity was poor at lower temperature (373 K) due to possibility of aniline remaining trapped as quaternary aniline salt (e.g. $[RNH_3]I$) [9] but above 393 K DPU selectivity remains high at ~98%. As expected the TOF was also found to increase with increase in temperature.

Effect of amount of aniline on activity of catalyst was investigated in the range of 60–100 mmol. It was found that the conversion

Table 6
Temperature effect (time 0.5 h).

Temperature (K)	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
373	6.6	88.2	56
393	24.7	97.0	228
423	49.2	97.2	454
443	61.9	96.8	568

Table 7
Effect of aniline amount on catalyst activity and selectivity (time 0.5 h).

Aniline (mmol)	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
60	43.1	94.9	388
74	52.7	93.6	468
91	61.0	99.6	577
100	66.6	97.9	619

Table 8
Effect of CO partial pressure on activity of $Pd(OAc)_2BipyDS$ catalyst (time 0.5 h).

CO pressure (bar)	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
37	24.6	96.5	225
46	36.9	96.4	337
55	45.2	97.5	417
64	53.6	95.7	487
72	65.1	97.4	601

of aniline and TOF increased with approximately first order dependence on aniline amount. The results obtained are shown in Table 7.

In order to investigate the effect of partial pressure of carbon monoxide (P_{CO}), partial pressure of oxygen was kept constant at 4.83 bar and P_{CO} was varied in the range of 37–72 bar. The purpose of study was to check for the oxygen starvation effect, i.e., increase in the demand for oxygen with increase in P_{CO}. Under such conditions reaction rates are expected to be influenced by mass-transfer, resulting in the lowering of TOF. Table 8 shows the effect of P_{CO} on conversion of aniline and on selectivity of DPU. The effect was found to be linear, and the TOF values increased with increase in P_{CO} indicating that the system is free of oxygen starvation.

The effect of partial pressure of oxygen was studied in the P_{O_2} range of 4.14–6.89 bar, while keeping the CO partial pressure at 64.12 bar (see Table 9). The partial pressure variation showed a consistent rise in the conversion of aniline as well as TOF values as the P_{O_2} was increased; the P_{O_2} effect on TOF was much pronounced compared to P_{CO} implying that the reaction is sensitive to P_{O_2}. This result confirmed that the reaction is in kinetically controlled regime. It may be noted here that the side reaction of CO oxidation to CO_2 is negligible (discussed later) and this does not seem to result in starvation of reactants during CO and O_2 partial pressure variation.

3.8. Catalyst recycle study

The recovery and reusability of the catalyst are obviously the major advantages of a two-phase catalytic reaction, even as the catalyst used can be tailor-made by manipulating the ligands. In the present study also, the reusability of the water-soluble palladium complex was critically checked. Table 10 shows the performance of $Pd(OAc)_2(BipyDS)$ for oxidative carbonylation of aniline up to 5 recycles. In each recycle, the aqueous phase containing catalyst was separated and used as such for the next reaction. The loss in the activity of the catalyst was negligible (see Table 10, TOF values in the range 210–191 h^{-1}). The aqueous solution of $Pd(OAc)_2(BipyDS)$ was found to be stable for several days from the observation that no discoloration or palladium precipitation was observed during this period. The organic phase recovered after the reaction was analyzed by AAS for the palladium content, and was found to contain <1 ppm

Table 9
Effect of oxygen partial pressure (time 0.5 h).

O_2 pressure (bar)	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
4.14	45.6	96.5	417
4.83	54.8	96.36	501
5.52	59.6	97.48	551
6.21	63.3	95.68	575

Table 10
Recycle of water soluble catalyst.

Recycle number	Aniline conversion (%)	DPU selectivity (%)	TOF (h^{-1})
0	97.1	91.2	210
1	93.7	92.8	206
2	92.8	90.5	199
3	91.5	89.7	195
4	90.5	90.3	194
5	87.3	92.2	191

palladium. Since the water-soluble complex was completely recovered after the reaction, it was expected that the sodium iodide promoter could be recovered as well at the end of the reaction. Therefore, a comparative account of the concentration of iodide in the initially charged as well as recovered aqueous phase was carried out using potentiometric estimation. It was observed, however, that the iodide was lost up to ~75% of its original loading from the aqueous phase at the end of second recycle. The loss was attributed to the iodine dissolved into the organic phase. The recycle reactions also indicated decline in aniline conversions when no fresh iodide was replenished into recycle experiments (data not shown).

3.9. CO oxidation

Carbon monoxide oxidation to carbon dioxide was found to take place under the conditions of our studies. To assess the formation of CO_2 side reaction, reaction was performed under standard conditions. A typical concentration–time profile under standard conditions for the aqueous-biphasic oxidative carbonylation of aniline for selective synthesis of 1,3-diphenylurea is shown in Fig. 2. The consumption of aniline throughout the reaction profile was found to be commensurate with the formation of the disubstituted urea, and no aniline derived by-products like oxamides or quinazolines were observed. However, the gas phase shows formation of carbon dioxide, which is well known for Pd metal catalyzed reactions involving CO, O_2 and water [15]. Separate experiments were carried out for a fixed reaction time to quantify the CO_2 formation in a biphasic system. Gas samples from the autoclave were analyzed at the end of each experiment. The formation of CO_2 by oxidation of CO takes place due to the nucleophilic attack of water molecule on the CO molecule coordinated to the transition metal centre [17]. It has also been reported that the formation of CO_2 increases in
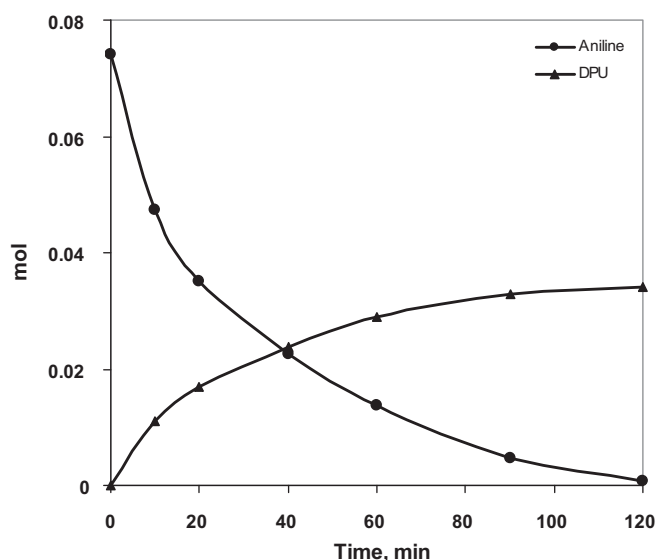
presence of diphenyl urea [7] resulting in increase in CO_2 formation with increase in reaction times, and such behavior was also observed in the present study. The CO_2 selectivity based on total CO consumed in the reaction was calculated, and it was found to be 6.9% (accounting dissolved CO_2 present in liquid phase).

3.10. Screening of amines

The applicability of the biphasic catalytic system was investigated for a range of amines, under standard reaction conditions (for details Table 11). Excellent activity and selectivity was observed when aniline, p-toluidine, p-anisidine, β-napthylamine and o-phenylene diamine (OPDA) were used as substrates (see Table 11, entries 1a, 2b, 3c, 5e, and 6f respectively). The aromatic diamine, OPDA was found to be an excellent substrate for the present study (see entry 6f). Primary aliphatic amines, such as benzylamine and butylamine, also gave excellent results (entries 7g, and 8h, TOF 192 and 218 h^{-1} respectively). Moderate activity of catalyst was observed when chloroaniline was used as a substrate (entry 4d, 48% yield of urea, TOF 114 h^{-1}). It was observed that in both the reactions, the aqueous layer containing the water-soluble catalyst retained a clear yellow color after the reaction. Also, no palladium precipitation was observed in these reactions. Primary diamines were also screened, to check for the formation of cyclic substituted ureas. Ethylene diamine and piperidine did not show any conversion under the similar experimental conditions (entries 9i and 12m). In order to understand whether the reason for the failure of these amines to react was a limitation of the biphasic catalyst system or the inherent low reactivity of the aliphatic diamine, a similar experiment was carried out using the conventional 5% Pd/C, NaI catalyst system, with toluene as the solvent and in absence of water in the reaction medium. In this case no gas absorption or conversion of amine was observed in the experiment, indicating that ethylene diamine, under the present set of experimental conditions, is not reactive for oxidative carbonylation (entries 9i and 10j). One of the possibilities is that, the bidentate ethylenediamine can strongly bind to electrophilic Pd(II) complex catalyst precursor forming a chelate thereby deactivating the catalyst. For dibenzylamine as the substrates, no reaction occurred under biphasic conditions (see entry 11k). From the amine screening studies, it was evident that the oxidative carbonylation of primary amines (both aliphatic as well as aromatic) results in satisfactory yields of corresponding urea in biphasic medium using a water-soluble catalyst, although secondary amines do not react under these conditions.

3.11. XPS analysis of fresh and spent catalyst

The X-ray photoelectron spectroscopy (XPS) was used for the analysis of fresh [Pd(OAc)$_2$(BipyDS)] and used catalyst. The X-ray actually removes the core orbital electrons of the elements at specific binding energies, which are fingerprints for particular oxidation states of the element. The XPS data also delivers some information about the immediate local electronic environment of the selected element incorporating the perturbation of the electron density due to the neighbouring functional groups and/or ligands. For obtaining XPS analysis of spent catalyst, aqueous phase containing water-soluble catalyst was recovered at the end of the 5th recycle experiment and was concentrated to dryness under vacuum on a rota-evaporator to obtain catalyst powder having amorphous nature. The freshly prepared Pd(OAc)$_2$(BipyDS) as well as the recovered catalyst were characterized by XPS for sulfur, nitrogen, carbon and palladium atoms for their respective binding energies (B.E.) and oxidation states. The B.E. values of the elements present in Pd(OAc)$_2$(BipyDS) (see Table 12 and B.E. values therein [18]; Fig. 3) catalyst compared well with literature values obtained from simi-

Fig. 2. Concentration–time profile in biphasic conditions.

Table 11
Screening of amines.[a]

Sr. No.	Amine (**1**)	Urea (**2**)	Amine conversion[b] (%)	Urea yield[c] (%)	TOF (h^{-1})	ν_{CO} (cm^{-1})
1a	aniline	(phenyl-NH)$_2$CO	94.5	87.8	208	1649
2b	4-methylaniline	(4-methylphenyl-NH)$_2$CO	96.8	94.4	224	1640
3c	4-methoxyaniline (H$_3$CO–)	(H$_3$CO–phenyl-NH)$_2$CO	98.3	79.6	189	1634
4d	4-chloroaniline (Cl–)	(Cl–phenyl-NH)$_2$CO	54.1	48.0	114	1633
5e	2-naphthylamine	(naphthyl-NH)$_2$CO	95.6	81.8	194	1632
6f	benzene-1,2-diamine	benzimidazol-2-one	96.6	84.4	200	1742
7g	benzylamine	(benzyl-NH)$_2$CO	96.8	81.1	192	1627
8h	butylamine	(butyl-NH)$_2$CO	97.4	92.1	218	1623
9i	ethylenediamine (H$_2$N–NH$_2$)	imidazolidin-2-one	N.R.	–	–	–
10j[d]	ethylenediamine (H$_2$N–NH$_2$)	imidazolidin-2-one	N.R.	–	–	–
11k	diphenylamine	[(phenyl)$_2$N–CO]$_2$	N.R.	–	–	–
12m	piperidine	(piperidyl)$_2$CO	N.R.	–	–	–

[a] Amine 74 mmol, Pd(OAc)$_2$(BipyDS) 0.078 mmol, water 10 ml, toluene 50 ml, NaI 0.90 mmol, T 423 K, pressure 68.9 bar, CO:O$_2$ 13:1, agitation 16.66 Hz, time 2 h.
[b] Determined by GC versus standards.
[c] Isolated yields, products characterized by IR, NMR and elemental analysis.
[d] Catalyst 5% Pd/C, solvent toluene; N.R.: no reaction.

lar Pd compounds [19,20]. The data for each element was corrected with respect to signal of the adventitious carbon at 285 eV. The binding energies of the other elements like N 1s, O 1s and S 2p also matched very well with the electronic configuration of the water-soluble complex. For example, O 1s state occurs at 533.1 eV, which is similar to the O^{-2} in an anion, e.g. carboxylate, or sulfonate; binding energy value for N 1s is 400.5 eV, which is slightly higher than the binding energy for N in pyridine (∼398.7 eV) due to the chelating through the N atom in the complex and consequent depletion of electron density. The binding energy value of sulfur 2p, which was found to be 169.3 eV was also matched closely with the S 2p

value in sulfate group like in Na$_2$SO$_4$, which is 169.6 eV. All these binding energy values indirectly support the molecular composition of the water-soluble Pd(OAc)$_2$(BipyDS) complex. A comparison of the XPS pattern of the recovered and fresh complex also confirms that the molecular nature of the complex and more particularly the oxidation state of palladium remains unchanged after the reaction. For pure Pd(OAc)$_2$ the 3d$_{5/2}$ state occurs at around 338.5 eV, while the palladium is in the 2+ oxidation state. The soft and resonating character of the OAc anion imparts lesser electron density to the Pd centre and hence Pd binding energy is slightly higher for Pd(OAc)$_2$. While in the case of other complexes of palladium coor-

**Table 12**
XPS data for Pd(OAc)$_2$(BipyDS) (values in eV).

B.E.	Elements					
	C	N 1s	O 1s	S 2p$_{3/2}$	Na 1s	Pd 3d$_{5/2}$
Uncorrected	288.9	404.4	537.0	173.2	1075.8	342.3
Corrected	285.0	400.5	533.1	169.3	1071.9	338.4
Literature[a]	285.0	400.0	532.1	169.6	1071.5	338.6

[a] B.E. values for comparison for elements are based on literature values [18]. However there is no XPS analysis report for Pd(OAc)$_2$(BipyDS) or analogous molecules for comparison.
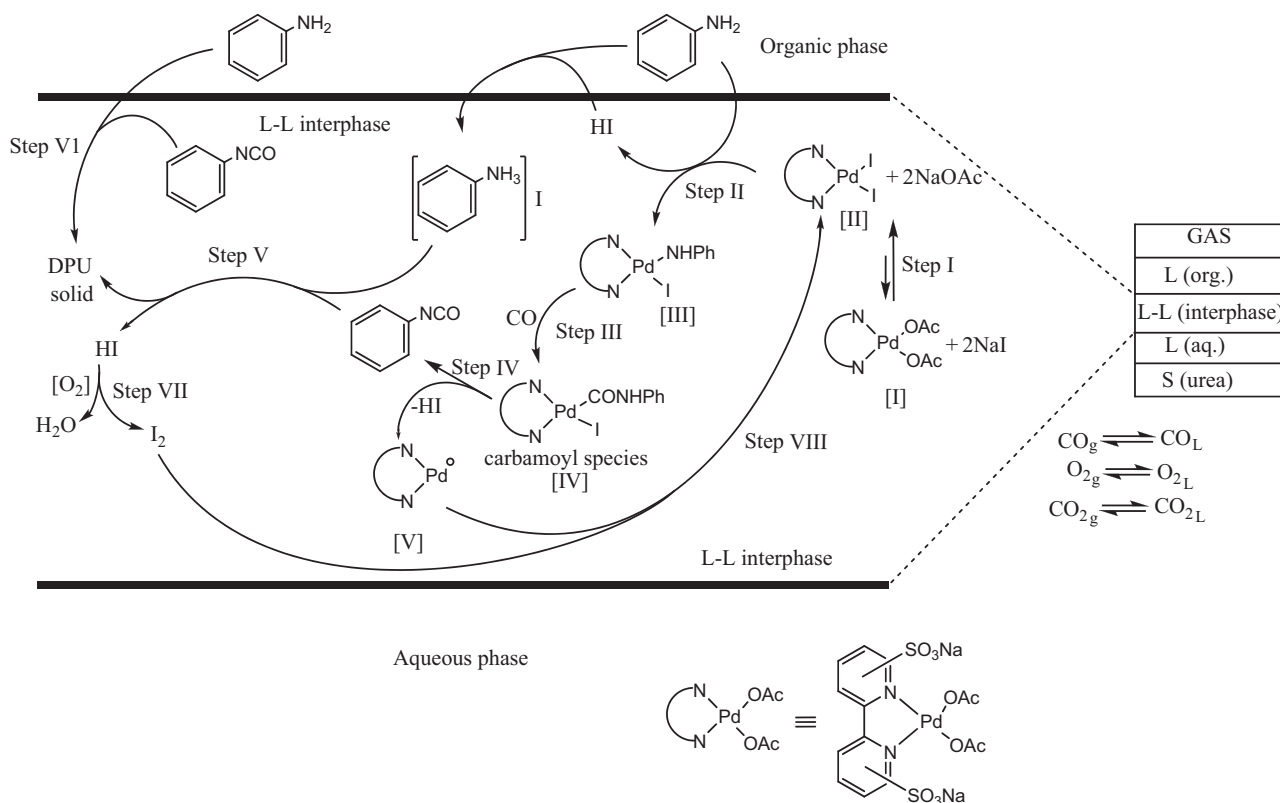
Scheme 3. Proposed mechanism of urea synthesis in a biphasic system.

dinated by 2,2′ bipyridine like in $PdCl_2(Bipy)$, $3d_{5/2}$ state occurs at lower values e.g. 338.0 eV. The $3d_{5/2}$ state in the $Pd(OAc)_2(BipyDS)$ occurs at 338.4 eV, indicating that the OAc group in the complex is intact, while the sulfonated bipyridine is coordinated to palladium. A characteristic band gap of 5.1 eV was also observed between the $3d_{5/2}$ and $3d_{3/2}$ signals of palladium for the palladium complex. Also, since no peak is observed at B.E. value of 335.7 eV, which is the characteristic B.E. value for metallic Pd $3d_{5/2}$ level, confirming that palladium is not present in zero oxidation state in both fresh and recovered catalyst [20].
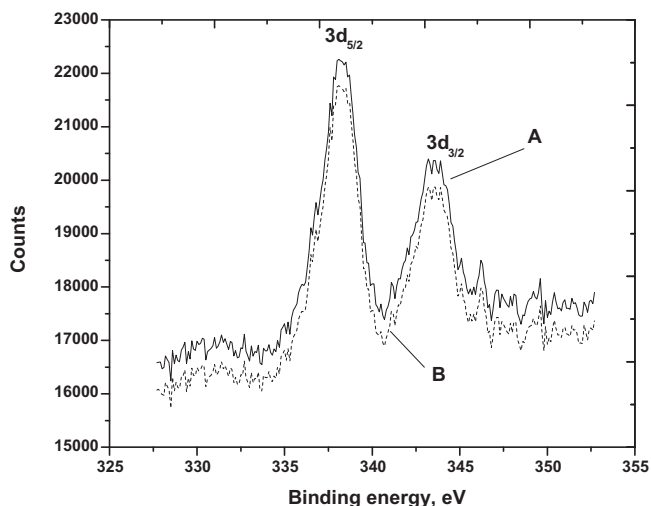
3.12. Plausible reaction mechanism

The chemistry and catalysis of oxidative carbonylation of amine to urea and carbamate has been recently reviewed by Gabriele et al. [2], McElwee-White and co-workers [21] and by Ragaini [22]. It is generally believed that, Pd catalyzed oxidative carbonylation of amine proceed via reduction of Pd(II) catalyst precursor in presence of CO by amine which in turned is oxidized. The reduced catalytic species is then re-oxidized in presence of oxidizing agents such as halide containing promoters and molecular oxygen regenerating the starting catalytic species [2,4,23,24]. When molecular oxygen is employed for abstraction of hydrogen of amine, water is generated [2,4,23–25]. The generated water competes with substrate amine giving rise to a side reaction of carbon monoxide oxidation to carbon dioxide which decreases the efficiency of the catalyst. Therefore, designing a catalytic system involving water as a solvent and at the same time minimizing CO oxidation is challenging. In order to minimize the CO oxidation, amine should be preferably activated rather than water by the catalyst. It is also known that in oxidation of CO to CO_2, presence of amine plays an important role, and in absence of amine it has been reported that CO_2 formation is particularly low [7]. The water soluble palladium catalyst presumably is more efficient towards amine carbonylation, compared to CO oxidation to carbon dioxide, particularly when sparingly water soluble aromatic amines are used. Also, small amount of quaternary amine (viz. monophenyl ammonium iodide in this case) formed during catalysis (see Scheme 3) is readily soluble in aqueous medium and it seems likely that this amine salt is more susceptible to be attacked by water-soluble Pd catalyst. Further under our reaction conditions of biphasic catalysis, we have not noticed any metal precipitation indicating that water soluble Bipy-DS ligand stabilize the Pd complex and Pd precipitation is prevented. Also, XPS analysis of spent catalyst does not indicate the presence of metal-

Fig. 3. XPS spectra of (A) fresh $Pd(OAc)_2BipyDS$ and (B) $Pd(OAc)_2BipyDS$ recovered.

lic Pd, therefore in the proposed mechanism formation of metallic Pd is not shown. The mechanism speculated in Scheme 3 is based on the formation carbamoyl species (species IV) as a key intermediate. A stoichiometric reaction between the Pd(OAc)$_2$(BipyDS) complex and NaI showed formation of the active catalytic intermediate species II (see Step I in Scheme 3) also reported previously by Mueller et al. [26]. It was observed that this reaction takes place at room temperature, which was evident from the immediate color change from faint yellow to dark brown upon addition of NaI. The species II interacts with aniline from organic phase saturated with CO generating HI and species III in which PhNH is coordinated to Pd (Step II). Species III adds on one molecule of dissolved CO from liquid phase forming carbamoyl species IV (Step III). As already suggested by Gabriele et al. [4,24] formation of phenyl isocyanate (Step IV) at this stage via β-H elimination from species IV with liberation of HI seems to be the most probable step. We do not however have any experimental evidence for formation of intermediate phenyl isocyanate under experimental conditions but it is postulated that phenyl isocyanate is formed at the interface (omega phase) [27], where it is isolated from water (phenyl isocyanate is highly reactive towards compounds containing active hydrogen such as water) and has a life-time just enough to react with [PhNH$_3$]I and aniline to form DPU (Steps V and VI respectively). The mechanism predicts that secondary amines cannot give isocyanate, this is also consistent with the experimental results that the secondary amines are not reactive towards urea synthesis [2,4,24,28]. Thus in Step IV, Pd(II) complex is reduced to (BipyDS)Pd^0 (species V) without metal precipitation. It is known that polycyclic nitrogen containing heterocyclic ligands have ability to stabilize the excess electron density on metal such as Pd^0 by accepting electrons from metal in low oxidation state [29]. Generated HI in Steps IV and V is then oxidized by molecular oxygen to eliminate water and iodine (Step VII), which according to what has been demonstrated by Gabriele et al. [2,4,24,30] oxidize the species V re-generating the active catalytic species II. DPU being sparingly soluble in aqueous as well as organic phase can be easily separated from reaction medium making the entire process simple in catalyst–product separation point of view.

4. Conclusion

In summary, the application of water-soluble palladium complex catalyst system under aqueous-biphasic reaction conditions has the advantage of easy recycle of catalyst and separation of product from the reaction medium. The effect of process parameters on DPU yield showed that the system is robust and free from any mass transfer effects under the conditions of this investigation. A plausible reaction mechanism has been proposed highlighting the role of iodide promoter.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2010.10.018.

References

[1] S.P. Gupte, R.V. Chaudhari, J. Catal. 114 (1988) 246–258.
[2] B. Gabriele, R. Mancuso, G. Salerno, M. Costa, Top. Organomet. Chem. 18 (2006) 239–271.
[3] (a) A.A. Kelkar, D.S. Kolhe, S. Kanagasabapathy, R.V. Chaudhari, Ind. Eng. Chem. Res. 31 (1992) 172–176;
(b) P. Giannoccaro, C.F. Nobile, G. Moro, A. Laginestra, C. Ferragina, M.A. Massucci, P. Patrono, J. Mol. Catal. 53 (1989) 349–357;
(c) Y.L. Sheludyakov, V.A. Golodov, Bull. Chem. Soc. Jpn. 57 (1984) 251–253;
(d) P. Giannoccaro, J. Organomet. Chem. 336 (1987) 271–278;
(e) P. Giannoccaro, Inorg. Chim. Acta 142 (1988) 81–84;
(f) I. Pri-Bar, H. Alper, Can. J. Chem. 68 (1990) 1544–1547;
(g) K. Hiwatari, Y. Kayaki, K. Okita, T. Ukai, I. Shimizu, A. Yamamoto, Bull. Chem. Soc. Jpn. 77 (2004) 2237–2250.
[4] B. Gabriele, G. Salerno, R. Mancuso, M. Costa, J. Org. Chem. 69 (2004) 4741–4750.
[5] F. Shi, J. Peng, Y. Deng, J. Catal. 219 (2003) 372–375.
[6] S.A.R. Mulla, S.P. Gupte, R.V. Chaudhari, J. Mol. Catal. 67 (1991) L7–L10.
[7] P. Giannoccaro, E. De Giglio, M. Gargano, M. Aresta, C. Ferragina, J. Mol. Catal. A: Chem. 157 (2000) 131–141.
[8] (a) S. Kanagasabapathy, S.P. Gupte, R.V. Chaudhari, Ind. Eng. Chem. Res. 33 (1994) 1–6;
(b) T.W. Leung, B.D. Dombek, J. Chem. Soc., Chem. Commun. (1992) 205–206;
(c) S.B. Halligudi, K.N. Bhatt, M.M.T. Khan, J. Mol. Catal. 68 (1991) 261–267.
[9] J.E. McCusker, A.D. Main, K.S. Johnson, C.A. Grasso, L. McElwee-White, J. Org. Chem. 65 (2000) 5216–5222.
[10] (a) S. Fukuoka, M. Chono, M. Kohno, J. Org. Chem. 49 (1984) 1458–1460;
(b) M. Liang, T.J. Lee, C.C. Huang, K.Y. Lin, J. Chin. Chem. Soc. 54 (2007) 885–892;
(c) P. Toochinda, S.S.C. Chuang, Ind. Eng. Chem. Res. 43 (2004) 1192–1199;
(d) S.S.C. Chuang, P. Toochinda, M.V. Konduru, ACS Symp. Ser. 766 (2001) 136–148;
(e) B.S. Wan, S.J. Liao, D.R. Yu, Appl. Catal. A: Gen. 183 (1999) 81–84;
(f) F. Shi, Y. Deng, J. Catal. 211 (2002) 548–551.
[11] F. Shi, Y. Deng, T. SiMa, H. Yang, Tetrahedron Lett. 42 (2001) 2161–2163.
[12] B.M. Bhanage, S.S. Divekar, R.M. Deshpande, R.V. Chaudhari, Org. Process Res. Dev. 4 (2000) 342–345.
[13] S. Anderson, E.C. Constable, K.R. Seddon, J.E. Turp, J.E. Baggott, M.J. Pilling, J. Chem. Soc., Dalton Trans. (1985) 2247–2261.
[14] G.J. ten Brink, I. Arends, R.A. Sheldon, Science 287 (2000) 1636–1639.
[15] H. Ishii, M. Goyal, M. Ueda, K. Takeuchi, M. Asai, Appl. Catal. A: Gen. 201 (2000) 101–105.
[16] F.A. Cotton, G. Wilkinson, M. Bochmann, C. Murillo, Advanced Inorganic Chemistry, 6th ed., John Wiley and Sons, Singapore, 2004, p. 551.
[17] M.N. Desai, J.B. Butt, J.S. Dranoff, J. Catal. 79 (1983) 95–103.
[18] (a) A.B. Volynsky, A.Y. Stakheev, N.S. Telegina, V.G. Senin, L.M. Kustov, R. Wennrich, Spectrochim. Acta Part B 56 (2001) 1387–1396;
(b) V. Bondarenka, Z. Martunas, S. Kaciulis, L. Pandolfi, J. Electron Spectrosc. Relat. Phenom. 131–132 (2003) 99–103;
(c) V.I. Nefedov, Y.V. Kokunov, Y.A. Buslaev, M.A. Porai-Koshits, M.P. Gustyakova, E.G. Il'in, Zh. Neorg. Khim. 18 (1973) 931–934.
[19] S.J. Kerber, J.J. Bruckner, K. Wozniak, S. Seal, S. Hardcastle, T.L. Barr, J. Vac. Sci. Technol. A 14 (1996) 1314–1320.
[20] G. Kumar, J.R. Blackburn, R.G. Albrtdge, W.E. Moddeman, M.M. Jones, Inorg. Chem. 11 (1972) 296–300.
[21] D.J. Diaz, A.K. Darko, L. McElwee-White, Eur. J. Org. Chem. (2007) 4453–4465.
[22] F. Ragaini, J. Chem. Soc., Dalton Trans. (2009) 6251–6266.
[23] P. Giannoccaro, C. Ferragina, M. Gargano, E. Quaranta, Appl. Catal. A: Gen. 375 (2010) 78–84.
[24] B. Gabriele, R. Mancuso, G. Salerno, M. Costa, Chem. Commun. (Cambridge, U.K.) (2003) 486–487.
[25] P.M. Maitlis, A. Haynes, B.R. James, M. Catellani, G.P. Chiusoli, J. Chem. Soc., Dalton Trans. (2004) 3409–3419.
[26] G. Mueller, M. Klinga, P. Osswald, M. Leskelae, B. Rieger, Z. Naturforsch. B: Chem. Sci. 57 (2002) 803–809.
[27] (a) D. Mason, S. Magdassi, Y. Sasson, J. Org. Chem. 56 (1991) 7229–7232;
(b) G.D. Yadav, Y.B. Jadhav, Langmuir 18 (2002) 5995–6002.
[28] P. Giannoccaro, J. Organomet. Chem. 470 (1994) 249–252.
[29] E.C. Constable, Adv. Inorg. Chem. 30 (1986) 69–121.
[30] (a) B. Gabriele, G. Salerno, M. Costa, G.P. Chiusoli, Curr. Org. Chem. 8 (2004) 919–946;
(b) B. Gabriele, G. Salerno, M. Costa, G.P. Chiusoli, J. Organomet. Chem. 687 (2003) 219–228;
(c) B. Gabriele, G. Salerno, M. Costa, Synlett (2004) 2468–2483;
(d) B. Gabriele, M. Costa, G. Salerno, G.P. Chiusoli, J. Chem. Soc., Perkin Trans. 1 (1994) 83–87.