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Short Communication

PEG-anchored rhodium polyether diphosphinite complex as an efficient homogeneous and recyclable catalyst for hydroaminomethylation of olefins

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ABSTRACT

A recyclable rhodium polyether diphosphinite complex anchored in polyethylene glycol [RhPEGD] was studied for hydroaminomethylation of various olefins with primary and secondary amines. The protocol was optimized with respect to various reaction parameters and the general applicability of catalyst for hydroaminomethylation of different functionalized olefins with corresponding amines was investigated. During the course of reaction, catalyst was soluble with reactants/products while could be quantitatively separated from reaction media in biphasic form by addition of anti-solvent on completion of reaction. The catalyst exhibited remarkable activity and was subsequently recycled up to five consecutive cycles.

1. Introduction

The hydroaminomethylation reaction has attracted a great attention for synthesis of amines finding large applications in pharmaceutical and chemical industries [1,2]. It is a tandem reaction involving hydroformylation of an olefin to an aldehyde followed by the reaction of resulting aldehyde with a primary or secondary amine to provide the corresponding enamine or imine and finally the intermediate is hydrogenated to amine (Scheme 1).

From economical and environmental point of view, one pot synthesis of amines from inexpensive feedstock like alkenes sounds to be a superior method over conventional ones which comprises of usually multi-step and less atom-efficient processes [3].

In 1949, W. Reppe discovered the hydroaminomethylation using stoichiometric amount of $Fe(CO)_5$ as a catalyst. Till mid of 1990s, relatively harsh conditions were employed to obtain good yield of corresponding amines from simple olefins with the aid of hydroaminomethylation reaction [4–7]. However in the past two decades, several other catalysts comprising of rhodium, ruthenium and bimetallic complexes were developed [8–10]. It is also noteworthy to mention that, the several other methodologies developed for hydroaminomethylation using homogeneous catalytic system suffer with the limitation of catalyst-product separation and catalyst recyclability. However, some investigations have been made in this regard and the possible outcome includes anchoring of homogeneous catalyst, either by using a liquid–liquid two phase system or by supported liquid phase catalysis [11,12]. On other hand, Alper and co-workers employed ionic diamine rhodium complex for hydroaminomethylation reaction but the system fails to recover an expensive rhodium metal catalyst on completion of the reaction [13,14]. Hence, still there lies a great scope in development of an efficient and facile metal complex catalyst with an industrially feasible separation strategy for the hydroaminomethylation reaction.

Considering the above issues, the aim of present work highlights use of liquid phase catalyst soluble in organic solvent thus retaining the merits of homogeneous systems with an additional advantage of biphasic separation strategy. On completion of reaction, the catalyst can be quantitatively separated in liquid form from the reaction mixture by addition of a volatile anti-solvent such as *n*-hexane which forms two phases and thus the liquid phase catalyst can be subsequently reused (Fig. 1). In continuation to our interest in application of biphasic separation methodology [15], we herein report a facile and highly efficient protocol for homogeneous liquid phase catalytic system for hydroaminomethylation reaction.

2. Experimental methods

2.1. Materials

All chemicals like olefins, amines, chlorodiphenylphosphine, $[Rh(acac)(CO)_2]$ and Xantphos were purchased from Sigma-Aldrich and Alfa Aesar. PEG-600 was supplied by S. D. Fine Chemicals India. All other reagents were of analytical grade and were used without further purification. Syn gas (CO and H_2, 1:1), with a purity of 99.9% was obtained from Rakhangi Gases Ltd., Mumbai, India.

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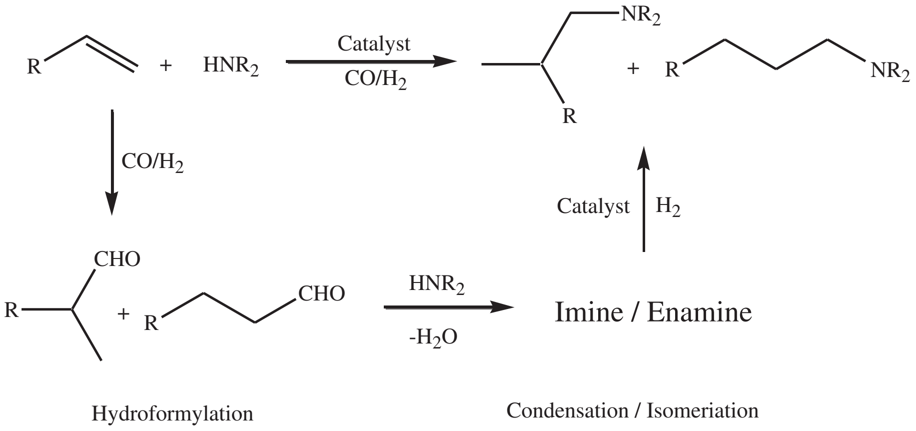


Scheme 1. Hydroaminomethylation of olefins.

2.2. General procedure for hydroaminomethylation

In a typical hydroaminomethylation procedure, to a high pressure reactor of 100 mL, olefin (2 mmol), amine (2 mmol) and toluene (10 mL) were added with polymeric RhPEGD-600 (2.5 μmol) (3.9 mg). The reactor was then flushed with nitrogen followed by syn gas (1:1 mixture of H_2 and CO gas) at room temperature; the reaction was then pressurized to 400 psi and was heated to 100 °C with stirring speed of 800 rpm. After completion of the reaction, the reactor was cooled to room temperature and remaining syn gas was carefully vented. The reaction mixture was analyzed by gas chromatography (Perkin Elmer, Clarus 400 GC) equipped with capillary column (30 m × 0.25 mm × 0.25 μm) and a flame ionization detector (FID). All the products obtained are well known in literature [8] and were confirmed by GC–MS analysis (Shimadzu, GCMSQP2010) equipped with Rtx wax capillary column (30 m length and 0.25 mm diameter).

2.3. Catalyst preparation and characterization

The polyether ligand α,ω-bis(diphenylphosphino)-poly(ethyleneglycol-200) [DPPPEG-200], α,ω-bis(diphenylphosphino)-poly(ethyleneglycol-400) [DPPPEG-400], α,ω-bis (diphenyl phosphino)-poly(ethyleneglycol-600) [DPPPEG-600], $Bu(OPPh_2)_2$ and Rh(I) carbonyl phosphinite complex [RhPEGD-600] were prepared by procedures reported in literature [15–19]. The complex $HRhCO(PPh_3)_3$ was also prepared by reported method [20,21]. ^{31}P NMR analysis of the diphosphinite ligand [DPPPEG-600] and polyether Rh metal complexes were carried out using a Varian 300 MHz instrument. Thermogravimetric analyses (TGA) of metal complex were performed using an SDT-Q600 instrument under N_2 atmosphere (refer supporting information).

2.3.1. Synthesis of α,ω-bis(diphenylphosphino)-poly(ethylene glycol) [DPPPEG-600] ligand

In an inert atmosphere, chlorodiphenylphosphine (2.3 g, 10.0 mmol) in THF (2.0 mL) was added slowly into a stirred solution of polyethylene glycol-600 (PEG-600) (5.0 mmol) and pyridine (Py) (0.8 g, 10.0 mmol) in THF (20 mL) at room temperature. The reaction mixture was stirred for 3 h at room temperature (30 °C). Precipitated Py.HCl was filtered off, and the THF solution was passed through a silica gel column to remove the dissolved Py.HCl. The ligand α,ω-bis(diphenylphosphino) poly(ethylene glycol-600) was obtained in 80% yield (4.0 g) after evaporation of THF under rotary evaporator.

^{31}P NMR (400 MHz, DMSO): δ 19.98 (s).

2.3.2. Synthesis of polyether phosphinite Rh (I) complex (RhPEGD-600)

A solution of $RhCl_3 \cdot H_2O$ (1 g, 3.8 mmol) in ethanol (30 mL) was added to a refluxing solution of polyether diphosphinite (11.4 mmol) in ethanol (150 mL). After 30 min, on dropwise addition of 40% aqueous formaldehyde (5 mL) the solution turned pale yellow. Further, addition of sodium borohydride (1 g) in ethanol to this hot mixture yielded the greenish yellow product, as described above with 70% yield.

^{31}P NMR (400 MHz, DMSO): δ 73.88 (d, $J_{(Rh,P)}$ 144 Hz).

2.4. Catalyst recyclability study

The catalyst was investigated for five consecutive recycles for hydroaminomethylation reaction using the above experimental procedure (described in Section 2.2). During recyclability study, additional PEG-600 (1 mL) was added for recovery of the catalyst. On completion of reaction, 20 mL *n*-hexane was added to the reaction mixture, which separated the lower catalyst-philic PEG phase from upper product phase. After phase separation PEG phase containing polyether Rh(I) catalyst was subjected to reuse by charging the same amount of substrate (2 mmol) in toluene as a solvent.

3. Results and discussion

The initial studies were conducted using RhPEGD-600 as a choice of catalyst for the hydroaminomethylation of cyclopentene with morpholine as a model reaction (Scheme 2).

Various reaction conditions for this transformation were extensively studied and the results obtained were summarized in Table 1. Initially, the reaction was studied at different temperatures in the

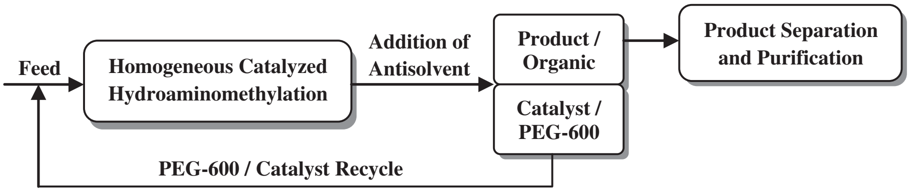
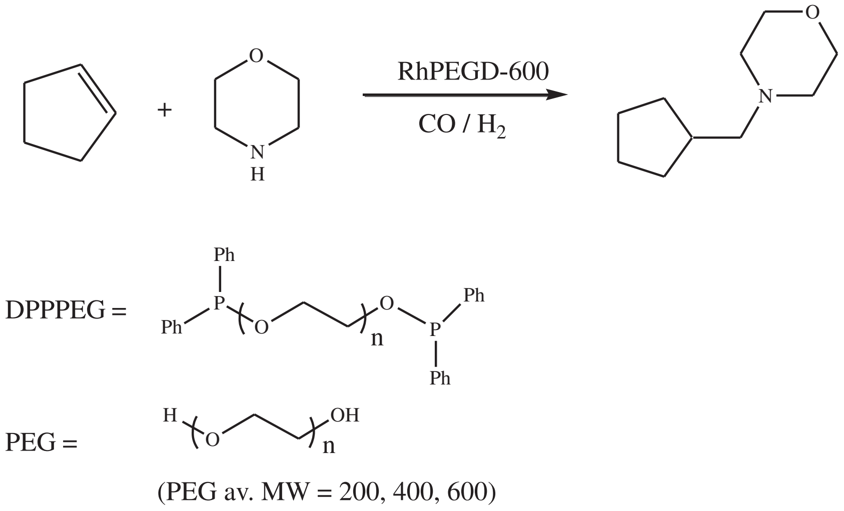


Fig. 1. Diagrammatic representation for catalyst separation and reusability.



Scheme 2. Hydroaminomethylation of cyclopentene with morpholine.

range of 80–120 °C (Table 1, entries 1–3) where 100 °C was found to provide the maximum conversion with high selectivity. However, with further increase in reaction temperature up to 120 °C, reduction of aldehyde to alcohol in small amount was observed. The influence of reaction time ranging from 2 to 6 h was studied and the best results were obtained within an appreciable period of 4 h (Table 1, entries 2, 4 and 5). Furthermore, the effect of syn gas pressure on reaction rate and selectivity of hydroaminomethylation reaction was studied in the range of 200–600 psi (Table 1, entries 2, 6 and 7). We observed that lowering the reaction pressure results in decrease of conversion as well as selectivity of desired product, whereas with further increase in pressure up to 600 psi did not have any prominent effect on the reaction outcome. While studying the hydroaminomethylation reaction at 400 psi of CO/H_2 (in 1:2 stoichiometric amounts), reduction of starting olefins (6%) was observed providing lower yield of desired product (Table 1, entry 8). Hence, further studies were carried out at 400 psi of CO/H_2 with 1:1 molar concentrations.

The influence of solvents on the hydroaminomethylation reaction was then investigated. We demonstrated the hydroaminomethylation reaction using PEG-600 as environmentally benign solvent but observed only 13% of conversion promising toluene as a best suitable solvent for the present reaction system (Table 1, entry 2, 9–10). In addition, we studied the substrate to rhodium mole ratio and observed that increasing the molar ratio from 400:1 to 800:1 had no significant effect on conversion and selectivity of desired product (Table 1, entries 2, 11) while further increase in substrate to rhodium mole ratio of 1600:1 decreased the conversion and selectivity of the reaction (Table 1, entry 12), this decrease in conversion and amine selectivity was due to decreases in the amount of catalyst from 2.5 μmol (Sub/Rh mole ratio 800:1) to 1.25 μmol (Sub/Rh mole ratio 1600:1). Hence, the optimized reaction conditions for the hydroaminomethylation using RhPEGD-600 catalyst were cyclopentene (2 mmol), morpholine (2 mmol), RhPEGD-600 (2.5 μmol), 400 psi CO/H_2 (1:1), temperature 100 °C for 4 h in toluene (10 mL) as a solvent.

Moreover, various Rh-phosphine and Rh-phosphinite catalysts were screened for hydroaminomethylation of cyclopentene with morpholine under optimized reaction conditions (Table 2, entries 1–6). Other phosphinite ligands such as DPPPEG-200, DPPPEG-400 and $Bu(OPPh_2)_2$ having similar steric and electronic properties to that of DPPPEG-600 revealed good selectivity toward amine formation however decrease in conversion was observed (Table 2, entries 2–4). Whereas, the bulky bidentate phosphine ligand like Xantphos provided the hydroaminomethylated product with comparatively low conversion (87%) and selectivity (72%) even after a prolonged reaction period of 6 h (Table 2, entry 5). On the other hand, extensively used hydroformylation catalyst $HRh(CO)(PPh_3)_3$ furnished good

Table 1
Hydroaminomethylation of cyclopentene using RhPEGD-600 catalyst.[a]

Entry	Solvent	Sub/Cat (mole ratio)	CO/H_2 (1:1) psi	Temp. (°C)	Time (h)	Conversion (%)[b]	Selectivity (%)[b]		
							Amine	Enamine	Hydrogenation
1	Toluene	800	400	80	4	68	92	7	1
2	Toluene	800	400	100	4	100	99	1	–
3	Toluene	800	400	120	4	100	95	1	4
4	Toluene	800	400	100	6	99	99	–	1
5	Toluene	800	400	100	2	79	98	2	–
6	Toluene	800	200	100	4	75	83	15	2
7	Toluene	800	600	100	4	100	96	1	3
8[c]	Toluene	800	400	100	4	100	94	–	6
9	*n*-Hexane	800	400	100	4	32	87	9	4
10	PEG-600	800	400	100	4	13	17	02	81
11	Toluene	400	400	100	4	100	100	–	–
12	Toluene	1600	400	100	4	87	97	1	2

[a] Reaction conditions: cyclopentene (2 mmol), morpholine (2 mmol), toluene (10 mL), 800 rpm.
[b] Conversion and selectivity were determined by GC analysis.
[c] CO/H_2 (1:2).

Table 2
Hydroaminomethylation of cyclopentene using various Rh catalysts: effect of ligands.[a]

Entry	Catalysts	Time (h)	Conversion (%)	Amine selectivity (%)[b]
1	RhPEGD-600	4	100	99
2	RhPEGD-400	4	93	98
3	RhPEGD-200	4	90	99
4	$Rh(acac)(CO)_2/2Bu(OPPh_2)_2$	4	89	98
5	$Rh(acac)(CO)_2$/2Xantphos	6	87	72
6	$HRh(CO)(PPh_3)_3$	4	82	92

[a] Reaction conditions: cyclopentene (2 mmol), morpholine (2 mmol), toluene (10 mL), catalyst (2.5 μmol), temperature (100 °C), CO/H_2 (1:1) (400 psi), 800 rpm.
[b] Conversion and selectivity were determined by GC analysis.

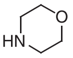
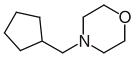
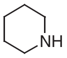
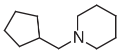
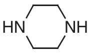
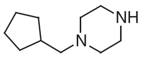
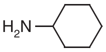
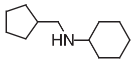
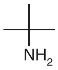
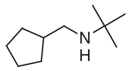
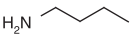
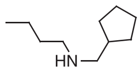
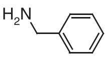
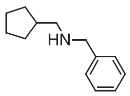
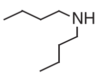
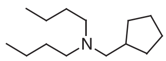
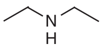
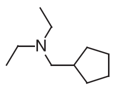
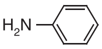
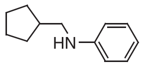
conversion and selectivity toward the desired product but was quite difficult to recycle in a homogeneous system (Table 2, entry 6). Hence, among the several screened rhodium based catalysts, RhPEGD-600 was found to be the best catalyst for hydroaminomethylation reaction providing admirable conversion and selectivity for the desired product.

In order to investigate the general applicability of developed protocol, we studied the hydroaminomethylation of cyclopentene with various primary or secondary amines (Table 3). Morpholine and piperidine smoothly reacted with cyclopentene providing excellent yield of desired product with remarkable selectivity toward the amine formation (Table 3, entries 1–2). However, piperazine undergoes the reductive amination resulting in mono-hydroaminomethylated as well as di-hydroaminomethylated product in ratio of 62:38 respectively (Table 3, entry 3). Various primary amines such as cyclohexyl amine, tertiary butyl amine, *n*-butyl amine and benzyl amine provided good to excellent yield of expected products with appreciable selectivity (Table 3, entries 4–7). Similarly, secondary aliphatic amines like dibutyl amine and diethyl amine also offered good yield of desired product (Table 3, entries 8–9). The reaction of cyclopentene with aromatic amine such as aniline provided considerable yield of hydroaminomethylated product (Table 3, entry 10).

The scope of developed catalytic protocol was further extended for hydroaminomethylation of various olefins as substrates with morpholine as amine source (Table 4, entries 1–5). The reaction of cyclohexene with morpholine resulted in good conversion and selectivity for the expected product (Table 4, entry 1). The reaction of morpholine with aromatic olefins such as styrene and 4-tert-butyl styrene offered good yield of hydroaminomethylated products (Table 4, entries 2–3), whereas Bicyclo[2.2.1]hept-2-ene also provided remarkable yield of desired product (Table 4, entry 4). Moreover, the linear aliphatic alkene such as 1-hexene also furnished a good conversion and selectivity toward amine formation (Table 4, entry 5).

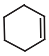
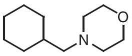
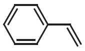
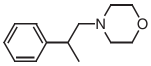
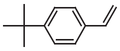
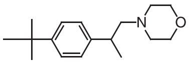
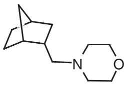
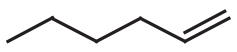
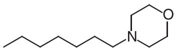
In consideration of economical view of the developed methodology, reusability of catalytic system was examined for hydroaminomethylation reaction of cyclopentene with morpholine. The organometallic complex prepared using PEG supported diphosphinite ligand is highly soluble in the PEG. PEG-600 (1 mL) was added along with starting material and toluene solvent during the study. The addition of PEG-600 makes the reaction medium viscous which decreases the yield of desired product at 100 °C, however at 120 °C excellent yield of desired product was obtained. Hence, 120 °C was used during the study. The RhPEGD-600 was found to be recycled for five consecutive runs with excellent catalytic activity and selectivity toward the formation of desired product (Table 5). In context, we performed the ICP-AES analysis of 1st and 5th recycle runs and observed only 0.01 ppm of rhodium in solution which revealed no significant leaching of rhodium.

Table 3
Hydroaminomethylation of cyclopentene with different amines.[a]

Entry	Amines	Major product	Conv. (%)	Amine selectivity (%)	Yield (%)[b]
1			100	99	99
2			99	99	98
3[c]			99	99	62 (62:38)
4			99	99	98
5			95	92	94
6			97	95	92
7			99	97	98
8			94	98	92
9			96	98	96
10			89	99	87

[a] Reaction conditions: cyclopentene (2 mmol), amine (2 mmol), toluene (10 mL), RhPEGD-600 (2.5 μmol), CO/H_2 (1:1) (400 psi), time (4 h), temperature (100 °C), 800 rpm.
[b] GC yield.
[c] Formation of monohydroaminomethylated and dihydroaminomethylated product.

Table 4
Hydroaminomethylation of different olefins with morpholine.[a]

Entry	Olefins	Major product	Conversion (%)	Amine selectivity (%)	Yield (%)[b]	n:i[b]
1			99	95	94	–
2			89	99	89	39:61
3			92	98	91	33:67
4			98	99	96	n.d.
5[c]			96	98	92	44:42:14

[a] Reaction conditions: olefin (2 mmol), morpholine (2 mmol), toluene (10 mL), RhPEGD-600 (2.5 μmol), CO/H_2 (1:1) (400 psi), reaction time (4 h), temperature (100 °C), 800 rpm, n.d. = not determined (Exo/Endo).
[b] GC yield, selectivity (n/i) was determined by GC analysis.
[c] Iso-product formed namely 4-(2-methyl-hexyl)-morpholine (42% yield) and 4-(2-ethyl-pentyl)-morpholine (14% yield).

Table 5
Catalyst recyclability study.[a]

Entry	RhPEGD-600 catalyst	Yield (%)[b]
1	Fresh	99
2	Recycle 1	99
3	Recycle 2	98
4	Recycle 3	98
5	Recycle 4	98
6	Recycle 5	98

[a] Reaction conditions: cyclopentene (2 mmol), morpholine (2 mmol), toluene (10 mL), PEG-600 (1 mL), RhPEGD-600 (2.5 μmol), CO/H_2 (1:1) (400 psi), time (4 h), temperature (120 °C), 800 rpm.
[b] GC yield.

4. Conclusion

In conclusion, we developed an efficient, homogeneous and reusable catalytic system for the hydroaminomethylation reaction. The present protocol is widely useful for one pot synthesis of secondary and tertiary amines from olefins via hydroformylation and subsequent reductive amination with CO and H_2 in the presence of polymeric rhodium diphosphinite as a catalyst. In addition, on completion of reaction the catalyst could be easily separated from the product and efficiently reused for five consecutive recycles without significant decrease in its catalytic activity. Thus, the developed catalytic system sounds to be more general with wider applicability for range of substrates appealing for its large scale application.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.catcom.2011.08.033.

References

[1] Y.Y. Wang, M.M. Luo, Q. Lin, H. Chen, X.J. Li, Green Chemistry 8 (2006) 545.
[2] P. Eilbracht, L. Barfacker, C. Buss, C. Hollmann, B.E. Kitsos-Rzychon, C.L. Kranemann, T. Rische, R. Roggenbuck, A. Schmidt, Chemical Reviews 99 (1999) 3329.
[3] T.E. Muller, M. Beller, Chemical Reviews 98 (1998) 675.
[4] M. Ahmed, R.P.J. Bronger, R. Jackstell, P.C.J. Kamer, P.W.N.M. van Leeuwen, M. Beller, Chemistry — A European Journal 12 (2006) 8979.
[5] M. Ahmed, A.M. Seayad, R. Jackstell, M. Beller, Journal of the American Chemical Society 125 (2003) 10311.
[6] A.F.M. Iqbal, Helvetica Chimica Acta 54 (1971) 1440.
[7] J.J. Brunet, D. Neibecker, F. Agbossou, R.S. Srivastav, Journal of Molecular Catalysis 87 (1994) 223.
[8] V.K. Srivastava, P. Eilbracht, Catalysis Communications 10 (2009) 1791.
[9] T. Rische, P. Eilbracht, Tetrahedron 55 (1999) 7841.
[10] B. Gall, M. Bortenschlager, O. Nuyken, R. Weberskirch, Macromolecular Chemistry and Physics 209 (2008) 1152.
[11] B. Zimmermann, J. Herwig, M. Beller, Angewandte Chemie, International Edition 38 (1999) 2372.
[12] B. Hamers, P.S. Bauerlein, C. Muller, D. Vogta, Advanced Synthesis and Catalysis 350 (2008) 332.
[13] K. Okuro, H. Alper, Tetrahedron Letters 51 (2010) 4959.
[14] T.O. Vieira, H. Alper, Chemical Communications 26 (2007) 2710.
[15] A.G. Panda, Y.P. Patil, P.J. Tambade, B.M. Bhanage, Industrial and Engineering Chemistry Research 49 (2010) 8360.
[16] A.G. Panda, M.D. Bhor, S.S. Ekbote, B.M. Bhanage, Catalysis Letters 131 (2009) 649.
[17] A.G. Panda, P.J. Tambade, Y.P. Patil, B.M. Bhanage, Reaction Kinetics, Mechanisms and Catalysis 99 (2010) 143.
[18] L. Hong, E. Ruckenstein, Journal of Molecular Catalysis 90 (1994) 303.
[19] L. Hong, E. Ruckenstein, Journal of the Chemical Society, Chemical Communications (1993) 1486.
[20] D. Evans, G. Yagupsky, G. Wilkinson, Journal of the Chemical Society A: Inorganic, Physical, Theoretical (1968) 2660.
[21] M. Matsumoto, M. Tamura, Journal of Molecular Catalysis 16 (1982) 195.