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Note

Palladium supported on poly(*N*-vinylimidazole) or poly(*N*-vinylimidazole-*co*-*N*-vinylcaprolactam) as a new recyclable catalyst for the Mizoroki–Heck reaction

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Abstract

A new catalytic system based on the palladium supported on poly(*N*-vinylimidazole) or poly(*N*-vinylimidazole-*co*-*N*-vinylcaprolactam) was investigated. High efficiency of the catalyst along with its recycling ability was demonstrated in the Mizoroki–Heck reaction.
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1. Introduction

The Mizoroki–Heck reaction is one of the widely used methods for the C–C bond formation, thus it is not surprising that the development of efficient catalysts allowing a wide range of reagents to react goes on for many years [1–7]. The problem mostly concerned by researchers is to combine high efficiency of the catalyst with the possibility of its easy separation from the reaction products [8]. The latter is especially important in the synthesis of biologically active compounds. Recovering of the catalyst is not less important taking into account high price of the palladium, normally used in the reaction.

Homogeneous palladium complexes with phosphine ligands [1,9] and "ligandless" complexes in the presence of additives stabilizing palladium clusters [10–15] are usually applied in the Mizoroki–Heck reaction. The major drawbacks of homogeneous catalysts are difficult separation from reaction products and impossibility of recycling. These problems do not arise in the case of heterogeneous catalysts. The latter consists of metal or metal complex immobilized on the surface of inorganic material [8,16–21] or polymer [8,22–30]. Usually such catalysts are less active and gradually lose their activity because of leaching. Major advances were achieved by the application of soluble polymers which possess groups capable of bonding metal. The activity of these catalytic systems is similar to that of homogeneous transition metal complexes, and they can be easily separated from products by changing temperature or solvent [31–33]. Normally phosphine group binds to the metal in such systems. Recently, *N*-donor molecules have been applied as ligands in palladium catalyzed reactions [34–41] because it allows to avoid toxic and readily oxidative unstable phosphines, and it has become possible to use this type of bonding with a polymer matrix [42–46].

2. Results and discussion

Here, we report a new catalytic system with PdCl$_2$ bonded to polymers such as poly(*N*-vinylimidazole) (PVI) or poly(*N*-vinylimidazole-*co*-*N*-vinylcaprolactam) (PVI-PVC) (30 mol% content of the latter monomer in the copolymer). The catalyst was investigated in a model

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Table 1
Reaction of phenyl iodide with *n*-butyl acrylate[a]

Entry	Polymer	Molar ratio PdCl$_2$:polymer[b]	Base	T (°C)	Time (h)	Yield[c,d] (%)
1	PVI	1:5	K$_2$CO$_3$	120	2	35[c]
2	PVI-PVC	1:5	K$_2$CO$_3$	120	2	99[d]
3	PVI	1:5	K$_2$CO$_3$	120	24	99[c]
4	PVI	1:5	K$_2$CO$_3$	100	8	39[c]
5	PVI-PVC	1:5	K$_2$CO$_3$	100	8	93[c]
6	PVI	1:10	K$_2$CO$_3$	120	4	5[c]
7	PVI-PVC	1:10	K$_2$CO$_3$	120	4	97[d]
8	PVI-PVC	1:50	K$_2$CO$_3$	120	17	68[d]
9	PVI-PVC	1:5	*n*-Bu$_3$N	120	2	99[c]
10[e]	PVI-PVC	1:5	K$_2$CO$_3$	120	2	65[c]

[a] Molar ratio of the reagents PhI:*n*-butyl acrylate:base:"Pd" = 1.0:1.2:2.0:0.01.
[b] To monomeric unit.
[c] By ^{1}H NMR.
[d] By GLC.
[e] 0.1% "Pd".

1 mol% "Pd"
2 eq K$_2$CO$_3$
DMF
100-120°C

"Pd" = PdCl$_2$ + polymer
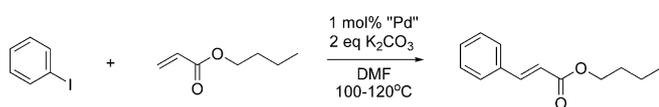
Scheme 1.

Mizoroki–Heck reaction with a number of substrates of different reactivity. The results of the reaction of phenyl iodide with *n*-butyl acrylate in DMF in the presence of 1 mol% of "Pd" and K$_2$CO$_3$ as a base are presented in Table 1 (see Scheme 1).

Obviously the reaction proceeds faster using the copolymer rather than the homopolymer. It completes after 2 h at 120 °C to produce *n*-butyl *trans*-cinnamate in a quantitative yield with the PVI-PVC copolymer-Pd system as the catalyst and gives just 35% yield of the product with the homopolymer case (entries 1 and 2). Nevertheless prolonged time of the reaction (24 h) allows to complete the reaction with the latter catalyst (entry 3). Decreasing temperature increases the reaction time (entries 4 and 5). Increasing polymer/palladium ratio also increases the reaction time (entries 6–8). The change of the base K$_2$CO$_3$ to *n*-Bu$_3$N does not influence the reaction (entry 9). Ten fold decrease of the palladium content to 0.1 mol% slows down the reaction

(entry 10), yield after 2 h at 120 °C drops to 68%, but the reaction remains stereoselective.

To clarify the morphology of the catalyst transmission, electron microscopy (TEM) studies were carried out. TEM images of the catalyst revealed the presence of palladium nanoparticles of 8–10 nm size with the even distribution inside the polymer matrix. XRD pattern additionally proved the existence of the palladium metal core in the particles (see Fig. 1).

Then we investigated the possibility of recycling the catalyst. After the reaction ran to completion, the polymer supported catalyst was precipitated by diethyl ether, separated from the solution containing the product, washed and used in the next reaction cycle with a new portion of reagents. Five consecutive cycles of the reaction showed that the catalyst did not lose its activity (Table 2) and could be completely recycled. We did not observe the palladium black formation in the reaction even after the fifth cycle.

The scope of applications of the catalytic system was investigated in the reaction with a number of aryl iodides and aryl bromides (see Scheme 2). In all cases the product was formed in high yield and with good stereoselectivity (Table 3). The reaction of *n*-butyl acrylate with such inactive substrate as phenyl bromide need the temperature to
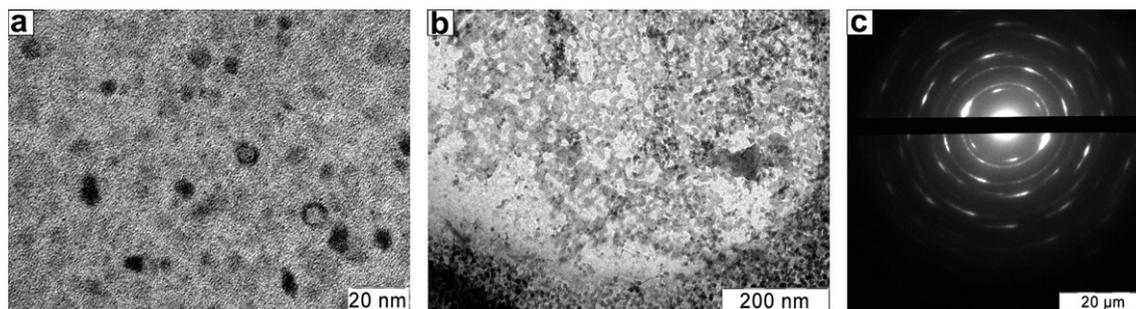
Fig. 1. Transmission electron micrographs of the catalytic system based on PdCl$_2$: PVI–PVC = 1:5 after the reaction of phenyl iodide with *n*-butyl acrylate (Table 1, entry 2) showing palladium nanoparticles (a) and the structure of the polymeric matrix (b), XRD pattern (c).

Table 2
Catalyst recycling in the reaction of PhI with *n*-butyl acrylate[a]

Cycle	Yield of the product[b] (%)	
	Molar ratio[c]	Molar ratio[c]
	PdCl$_2$:PVI-PVC = 1:5	PdCl$_2$:PVI-PVC = 1:10
1	99	97
2	99	99
3	91	96
4	94	92
5	98	92

[a] Molar ratio of the reagents PhI:*n*-butyl acrylate:K$_2$CO$_3$:"Pd" = 1.0:1.2:2.0:0.01. Reaction conditions: DMF, 120 °C, 2 h in the case of PdCl$_2$:PVI-PVC = 1:5 and 4 h in the case of PdCl$_2$:PVI-PVC = 1:10.
[b] By GLC.
[c] To monomeric unit.
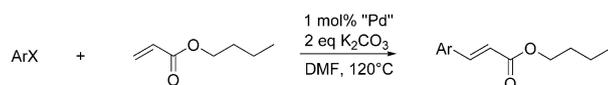
"Pd" = PdCl$_2$/PVI-PVC=1:5

Scheme 2.

Table 3
Reactions of *n*-butyl acrylate with aryl halides[a]

ArX	Reaction time (h)	Yield of the product[b] (%)
p-MeOC$_6$H$_4$I	4	86
p-MeC$_6$H$_4$I	3	93
p-MeC(O)C$_6$H$_4$I	2	91
p-MeO$_2$CC$_6$H$_4$I	4	95
p-MeC(O)C$_6$H$_4$Br	2	95
p-NCC$_6$H$_4$Br	2	94
C$_6$H$_5$Br	8 (at 140 °C)	64
C$_6$H$_5$Br	24 (at 140 °C)	84
C$_6$H$_5$Br (+100% *n*-Bu$_4$NBr)	8	83[c]

[a] Molar ratio of the reagents ArX:*n*-butyl acrylate:K$_2$CO$_3$:PdCl$_2$:PVI-PVC = 1.0:1.2:2.0:0.01:0.05. Reaction conditions: DMF, 120 °C.
[b] Isolated yield.
[c] By ^{1}H NMR.

be increased to 140 °C, but the addition of tetrabutylammonium bromide allows to decrease the temperature back to 120 °C.

The recycling of the catalyst in the reaction with aryl bromide was investigated and no loss in activity was noticed after five consecutive cycles (see Scheme 3).

The reaction with less active styrene proceeds considerably slower compared to *n*-butyl acrylate. Higher temperature

"Pd" = PdCl$_2$/PVI-PVC=1:5

1-st cycle:	99%	
2-nd cycle:	99%	Yield by
3-rd cycle:	93%	^{1}H NMR
4-th cycle:	92%	
5-th cycle:	98%	

Scheme 3.

"Pd" = PdCl$_2$/PVI-PVC=1:5

With Bu$_4$NBr

120°C, 6 hrs.	44%	4%
140°C, 6 hrs.	77%	9%
120°C, 6 hrs.	85%	5%

Scheme 4.

"Pd" = PdCl$_2$/PVI-PVC=1:5

120°C, 2 hrs.   97%   3%
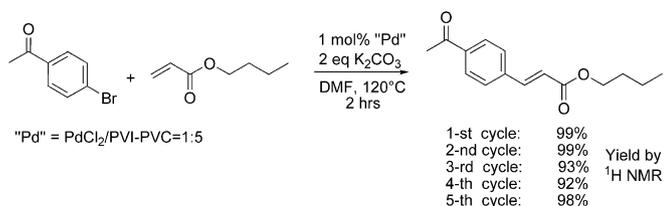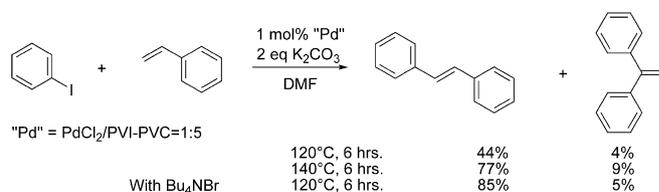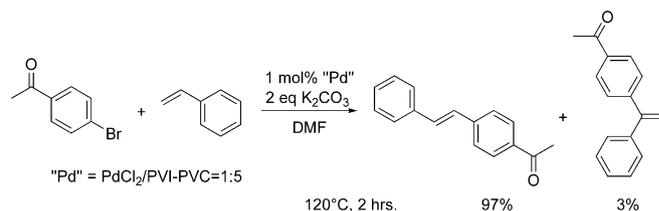
Scheme 5.

ture and longer time are needed to obtain a reasonable yield of *trans*-stilbene, while stereoselectivity becomes lower due to the formation of the second product 1,1-diphenylethene. However, the addition of the *n*-Bu$_4$NBr improves the result (see Scheme 4).

Surprisingly, the reaction of styrene with *p*-acetylphenyl bromide, which is normally a less active substrate compared to phenyl iodide, proceeds much smoother (see Scheme 5).

3. Conclusion

In conclusion we investigated a new recyclable catalytic system comprising palladium(II) chloride and poly(*N*-vinylimidazole) and poly(*N*-vinylimidazole-*co*-*N*-vinylcaprolactam). The high efficiency and stability of the system was shown in the model Mizoroki–Heck reaction with a number of active (aryl iodides and *n*-butyl acrylate) and less active (aryl bromides and styrene) substrates. The catalyst can be used multiple times in repeating cycles and its activity was shown to be constant.

4. Experimental

4.1. General procedure

Most of reagents were supplied by Lancaster. Solvents were purified by standard technique. All reactions were carried out under argon atmosphere and were monitored by thin-layer chromatography (TLC) using silica gel 60 F$_{254}$ plates (Merck). Column chromatography was performed on Merck silica gel 60 (0.040–0.063 mm) for the isolation of products and on Alfa Aesar silica gel (60–200 nm) for qualitative GLC and ^{1}H NMR analysis samples.

GLC analysis was performed on chromatograph Hewlett Packard 5890 Series II Plus with capillary column HP-1701 (15 m length, 0.32 mm diameter, 0.25 µm phase layer thickness) using hexadecane as an internal standard.

^{1}H NMR spectra were obtained using Bruker AMX-400 spectrometer at 400 MHz in CDCl$_3$. Qualitative ^{1}H NMR analysis was performed using dimethyl fumarate as an internal standard.

4.2. Polymers preparation

4.2.1. Poly(N-vinylimidazole)

Argon was bulbed through a solution of *N*-vinylimidazole in water (the volumetric concentration of the monomer-30%) and AIBN as the initiator (1%) for 20 min, then the reaction mixture was maintained during 140 h at 50 °C. After cooling to ambient temperature, the mixture was diluted in 15 times with water, subjected to dialysis and liophilic drying. The yield was >80%. Molar mass was determined by the sedimentation analysis. MM = 75 300.

4.2.2. Copolymer of N-vinylimidazole and N-vinylcaprolactam (30%)

Argon was bulbed through a solution of monomers in ethanol (the general volumetric concentration of the monomers −30%) and AIBN as the initiator (0.1%) for 20 min, then the reaction mixture was maintained during 48 h at 50 °C. After cooling to ambient temperature, the mixture was diluted in 5 times with ethanol and poured out at intensive stirring in diethyl ether. White solid was filtered, dissolved in distilled water, subjected to dialysis and liophilic drying. The yield was >80%. Molar mass was determined by the light scattering analysis. MM ≈ 20 000.

4.3. Mizoroki–Heck reaction

4.3.1. Mizoroki–Heck reaction (GLC and ^{1}H NMR analysis)

0.1 or 1 mL of 2×10^{-6} M H$_2$PdCl$_4$ solution in EtOH, prepaired by the addition of the excess of HCl solution in dioxane to the PdCl$_2$ and stirring for 3 h at 20 °C, was placed into the reactor and evaporated in vacuum. Then 1 mL of 2×10^{-4} M aryl halide solution in DMF, containing 0.1 mmol/mL hexadecane (internal standard), K$_2$CO$_3$ (0.4 mmol), polymer (5, 10 or 50 mol% in relation to Pd) and *n*-butyl acrylate or styrol (0.24 mmol) were added. The mixture was stirred at 100–140 °C. Then diethyl ether (4 mL) was added and the reaction mixture was stirred for 15 min. The solution was separated and the precipitate was washed by diethyl ether (2×2 mL). The precipitate was dried and used as a catalyst in the subsequent cycles, if it was required. Combined organic phases were passed through a silica filter, which then was washed with dichloromethane (5 mL). The resulting solution was used as a sample for GLC analysis. For the ^{1}H NMR analysis dimethyl fumarate as an internal standard was added.

4.3.2. Mizoroki–Heck reaction (isolating of pure product)

PdCl$_2$ (0.015 mmol), copolymer of *N*-vinylimidazole and *N*-vinylcaprolactam (0.075 mmol), aryl halide (1.5 mmol), K$_2$CO$_3$ (3.0 mmol), DMF (7 mL) were mixed in a reaction flask and *n*-butyl acrylate or styrol (1.8 mmol) was added. The reaction mixture was stirred at 120–140 °C. After cooling to ambient temperature, the reaction mixture was poured in water (20 ml) and extracted with CH$_2$Cl$_2$ (3×15 mL). The combined organic phases were dried over Na$_2$SO$_4$, filtered and evaporated in vacuum. The products were isolated by flash chromatography using petrol ether or CH$_2$Cl$_2$ or their mixture as eluents. The structure of products was determined by ^{1}H and ^{13}C NMR.

Acknowledgements

References

[1] E. Negishi (Ed.), Handbook of Organopalladium Chemistry for Organic Synthesis, Wiley, New York, 2002.
[2] J.G. de Vries, Dalton Trans. (2006) 421–429.
[3] F. Alonso, I.P. Beletskaya, M. Yus, Tetrahedron 61 (2005) 11771–11835.
[4] V. Farina, Adv. Synth. Catal. 346 (2004) 1553–1582.
[5] A.F. Littke, G.C. Fu, Angew. Chem. 114 (2002) 4350–4386.
[6] N.J. Whitcombe, K.K. Hii, S.E. Gibson, Tetrahedron 57 (2001) 7449–7476.
[7] I.P. Beletskaya, A.V. Cheprakov, Chem. Rev. 100 (2000) 3009–3066.
[8] B.M. Bhanage, M. Arai, Catal. Rev. 43 (2001) 315–344.
[9] J. Tsuji, Palladium Reagents and Catalysts, Wiley, Chichester, 1995.
[10] R.K. Arvela, N.E. Leadbeater, J. Org. Chem. 70 (2005) 1786–1790.
[11] M.T. Reetz, J.G. de Vries, Chem. Commun. (2004) 1559–1563.
[12] A.H.M. de Vries, J.M.C.A. Mulders, J.H.M. Mommers, H.J.W. Henderickx, J.G. de Vries, Org. Lett. 5 (2003) 3285–3288.
[13] M. Moreno-Mañas, R. Pleixats, Acc. Chem. Res. 36 (2003) 638–643.
[14] M. Beller, H. Fischer, K. Kühlein, C.-P. Reisinger, W.A. Herrmann, J. Organomet. Chem. 520 (1996) 257–259.
[15] M.T. Reetz, R. Breinbauer, K. Wanninger, Tetrahedron Lett. 37 (1996) 4499–4502.
[16] M. Seki, Synthesis (2006) 2975–2992.
[17] Á. Molnár, A. Papp, Synlett (2006) 3130–3134.
[18] M.L. Kantam, S. Roy, M. Roy, M.S. Subhas, P.L. Likhar, B. Sreedhar, B.M. Choudary, Synlett (2006) 2747–2750.
[19] C.M. Crudden, M. Sateesh, R. Lewis, J. Am. Chem. Soc. 127 (2005) 10045–10050.
[20] A. Papp, G. Galbács, Á. Molnár, Tetrahedron Lett. 46 (2005) 7725–7728.
[21] K. Yu, W. Sommer, J.M. Richardson, M. Weck, C.W. Jones, Adv. Synth. Catal. 347 (2005) 161–171.
[22] Y. Uozumi, Topics Current Chem. 242 (2004) 77–112.
[23] M. Králik, A. Biffis, J. Mol. Catal. A 177 (2001) 113–138.
[24] H. Hagio, M. Sugiura, S. Kobayashi, Org. Lett. 8 (2006) 375–378.
[25] B. Altava, M.I. Burguete, E. García-Verdugo, N. Karbass, S.V. Luis, A. Puzary, V. Sans, Tetrahedron Lett. 47 (2006) 2311–2314.
[26] F. Churruca, R. SanMartin, I. Tellitu, E. Domínguez, Synlett (2005) 3116–3120.

[27] P.G. Steel, C.W.T. Teasdale, Tetrahedron Lett. 45 (2004) 8977–8980.
[28] Y.M.A. Yamada, K. Takeda, H. Takahashi, S. Ikegami, Tetrahedron Lett. 44 (2003) 2379–2382.
[29] M.M. Dell'Anna, P. Mastrorilli, F. Muscio, C.F. Nobile, G.P. Suranna, Eur. J. Inorg. Chem. (2002) 1094–1099.
[30] Z. Zhang, Y. Pan, H. Hu, T. Kao, Synthesis (1991) 539–542.
[31] D.E. Bergbreiter, J. Li, Topics Current Chem. 242 (2004) 113–176.
[32] D.E. Bergbreiter, S.D. Sung, Adv. Synth. Catal. 348 (2006) 1352–1366.
[33] C.-A. Lin, F.-T. Luo, Tetrahedron Lett. 44 (2003) 7565–7568.
[34] J.-H. Li, X.-C. Hu, Y. Liang, Y.-X. Xie, Tetrahedron 62 (2006) 31–38.
[35] J.-H. Li, D.-P. Wang, Y.-X. Xie, Synthesis (2005) 2193–2197.
[36] C. Nájera, J. Gil-Moltó, S. Karlström, L.R. Falvello, Org. Lett. 5 (2003) 1451–1454.
[37] G.A. Grasa, R. Singh, E.D. Stevens, S.P. Nolan, J. Organomet. Chem. 687 (2003) 269–279.
[38] T. Kawano, T. Shinomaru, I. Ueda, Org. Lett. 4 (2002) 2545–2547.
[39] J. Silberg, T. Schareina, R. Kempe, K. Wurst, M.R. Buchmeiser, J. Organomet. Chem. 622 (2001) 6–18.
[40] M.R. Buchmeiser, T. Schareina, R. Kempe, K. Wurst, J. Organomet. Chem. 634 (2001) 39–46.
[41] M.R. Buchmeiser, K. Wurst, J. Am. Chem. Soc. 121 (1999) 11101–11107.
[42] H.-X. Zhang, C.-C. Luo, T. Jin, X.-P. Luo, Synth. Commun. 37 (2007) 191–197.
[43] S. Pathak, M.T. Greci, R.C. Kwong, K. Mercado, G.K.S. Prakash, G.A. Olah, M.E. Thompson, Chem. Mater. 12 (2000) 1985–1989.
[44] J. Le Bars, U. Specht, J.S. Bradley, D.G. Blackmond, Langmuir 15 (1999) 7621–7625.
[45] S. Klingelhöfer, W. Heitz, A. Greiner, S. Oestreich, S. Förster, M. Antonietti, J. Am. Chem. Soc. 119 (1997) 10116–10120.
[46] J. Gil-Moltó, S. Karlström, C. Nájera, Tetrahedron 61 (2005) 12168–12176.