Hydroxycarbonylation of Olefins and Alcohols in Ionic Liquids

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Abstract

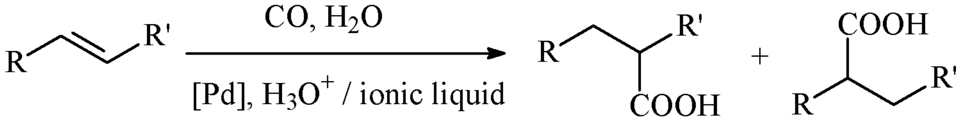
Palladium-catalysed hydroxycarbonylation of olefins and alcohols proceeds in ionic liquid media. Terminal and internal olefins, cyclohexene, styrene, methanol, ethanol, n-butanol, cyclohexanol, benzyl alcohol and 1-phenylethanol were tested as substrates for the reaction. A number of molten salts were applied as a reaction medium and tetrabutylammonium bromide (m.p. 103°C) seemed to be the best. Carbon monoxide pressure of 2 MPa and reaction temperature of 110°C are suitable conditions to furnish the reaction in 2 hours in the presence of palladium acetate as a precursor. Triphenylphosphine added as a ligand reduces reaction rate. The critical role of counter anion in molten salt was also recognised. Yield of acids decreased in the order: $Br^- > Cl^- > BF_4^- \approx PF_6^-$. A two-route reaction scheme is proposed to explain the regularities of styrene and 1-phenylethanol hydroxycarbonylation. The catalytic system can be used repeatedly by simple extraction of products with diethyl ether. Nine cycles were carried out without loss of activity.

Introduction

Transition metal catalysed carbonylation of olefins and alcohols is direct one step route for the synthesis of carboxylic acids and esters [1–10]. In particular, commercial non-steroidal anti-flammatory drugs ibuprofen and naproxen may be synthesised by hydroxycarbonylation of 1-arylethanol and derivatives [11–13]. However, separation of the product from the catalyst is a serious problem in hydroxycarbonylation as well as in other homogeneous catalytic reactions. A number of ways of overcoming this drawback have been proposed, in particular, immobilising catalyst in water [14], perfluorated solvents [15], the use of $scCO_2$ [16]. Another promising class of new media are molten salts or ionic liquids (ILs) [17]. They are good solvents for transition metal complexes and are poorly miscible with non-polar organics such as paraffins and ethers, allowing the formation of two-phase systems. Ionic liquids are generally thermally stable and chemically resistant. Being composed entirely of ions, they possess negligible vapour pressures. This makes them environmentally benign media for industrial use. Wide range of possible cations and anions means that their properties may be directly controlled. Despite short history of ionic liquids in chemistry, there have been numerous publications on their employment as a reaction media in numerous organic and catalytic reactions [18–25]. However, only a few reports were devoted to carbonylation of olefins and alcohols in molten salt media [26–30]. This is why these reactions were carefully studied by us and basic regularities were revealed. Appropriate reaction scheme was drawn in agree with observed facts.

Hydroxycarbonylation of olefins

The hydroxycarbonylation of olefins results in the corresponding acids. The reaction proceeds under CO pressure and requires an acid promoter:



R = Alk, Ph
R’ = H, Alk

We conducted the reaction in a 50-mL steel reactor equipped with Hastelloy liner, a magnetic stirrer and an electric furnace. Olefin (4 mmol), catalyst (5 mol%), acid promoter, water and IL were charged. The reactor was purged several times with CO, sealed, and kept at the required constant temperature. Then, CO was admitted up to the required pressure and the stirrer was turned on. The pressure in the reactor was maintained automatically. After 2 h, the reactor was cooled to ambient temperature and the reaction mixture was unloaded, extracted with ether, and analysed by GLC.

Tab. 1 and Fig. 1 represent typical results on olefin hydroxycarbonylation in tetrabutylammonium bromide (TBAB) medium. The reaction with aliphatic olefins in most cases resulted in more than two isomeric acids. This is due to the migration of the double bond in the substrate molecule in the presence of strong mineral acid. Primary olefins are more reactive then secondary ones due to steric hindrance of alkyl substituents. We tested HCl and TsOH as acid promoters. The yields of fatty acids are somewhat higher in the presence of HCl. Thus, upon the carboxylation of decene-1, the yield of acids was 91 and 86% in the presence of HCl and TsOH, respectively, whereas the carboxylation of tetradecene-7 led to 57 and 50% yield, respectively.

Table 1. Hydroxycarbonylation of olefins in TBAB medium [a]

Olefin	Promoter	Conversion, %	Yield of acids, % (GLC)		
			linear	2-Me-subst.	total
Heptene-1	HCl	100	42	40	91
Octene-1	–"–	100	42	38	88
Octene-2	–"–	86	15	43	82
Nonene-1	–"–	99	42	38	91
Decene-1	–"–	100	44	38	91
–"–	TsOH	99	41	34	86
Hexadecene-1	HCl	97	38	40	89
Tetradecene-7	–"–	62	–	56 [b]	57
–"–	TsOH	55	–	48 [b]	50
Cyclohexene	–"–	100	–	–	90
Styrene [c]	HCl	94	41	42	83

[a] 4 mmol olefin, 0.02 mmol $Pd(OAc)_2$, 0.8 mmol acidic promoter, 20 mmol H_2O, 2 g TBAB. P 5 MPa, T 110°C, 2 h. [b] 2-hexylpelargonic acid. [c] 5 mL of heptane were added.

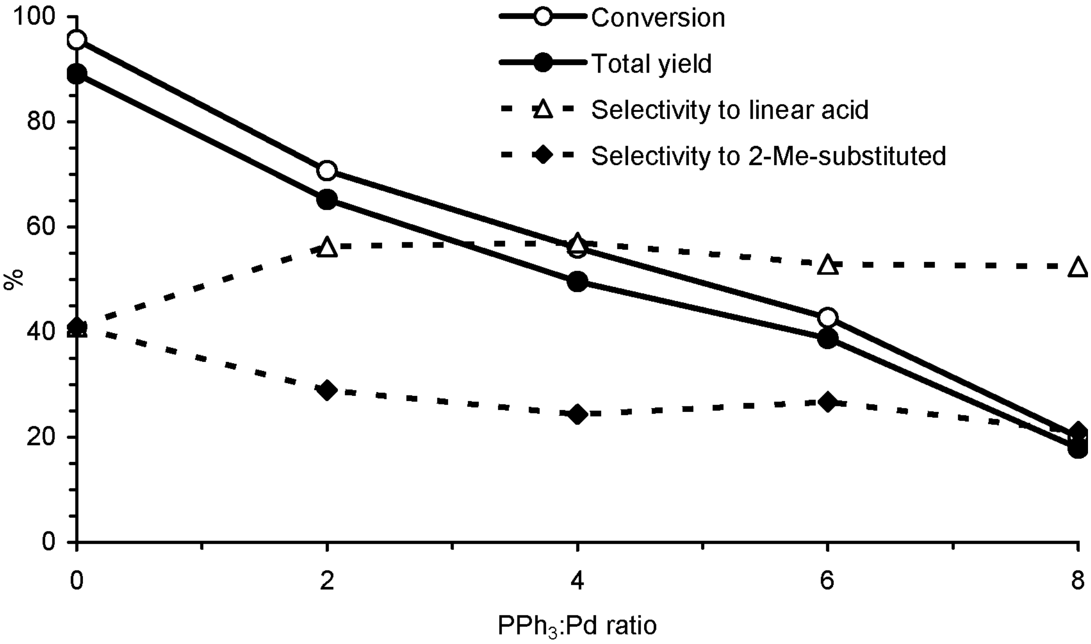


Figure 1. Effect of PPh_3 adding on dodecene-1 hydroxycarbonylation. Conditions: see Tab. 1.

Using $Pd(OAc)_2$ as a catalyst led to high, up to quantitative, conversion of olefins and high selectivity toward the target carboxylic acids. Moreover, in TBAB medium these ligand-free catalysts seemed to be more suitable than traditionally used phosphine complexes such as $PdCl_2(PPh_3)_2$ and $Pd(PPh_3)_4$. Palladium complexes with bidentant ligands such as $PdCl_2(dppe)$ и $PdCl_2(dppb)$ were far less reactive than $PdCl_2(PPh_3)_2$ in styrene carbonylation. Adding PPh_3 to the reaction mixture with $Pd(OAc)_2$ catalyst also decreased carbonylation rate. The higher PPh_3:Pd ratio, the lower fatty acids yield. Notably, selectivity to linear acid increased upon addition of 2 mole PPh_3 per mol Pd. Further increase PPh_3 amount had no effect on regioselectivity (Fig. 1).

The role of anion in IL is certainly important. We conducted a series of experiments admixing tetrabutylammonium chloride (TBAC) or iodide (TBAI) to TBAB. Total weight of IL was the same. Adding both Cl^- and I^- to the reaction mixture render catalyst less active judging by olefin conversion and total acids yield (Fig. 2).

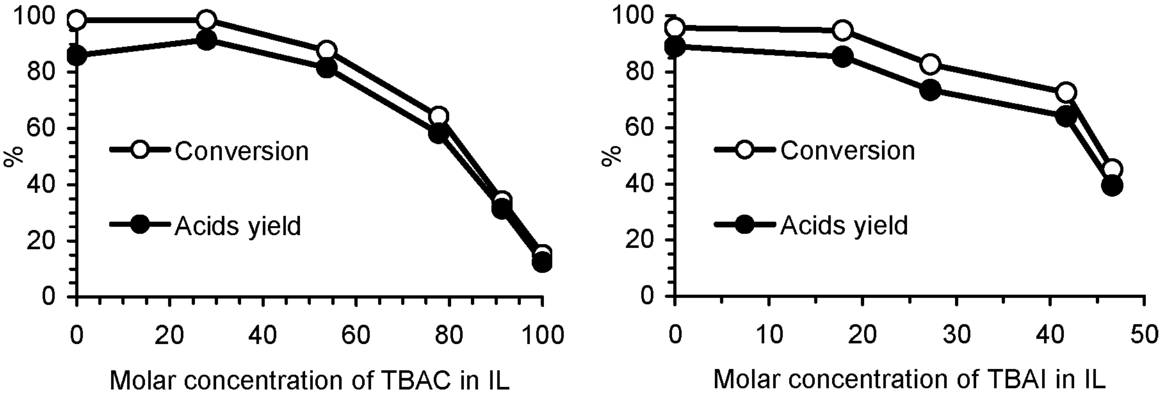
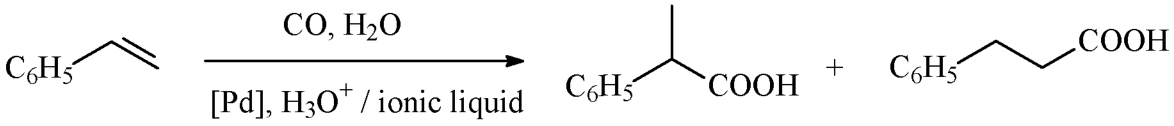


Figure 2. Hydroxycarbonylation of dodecene-1 in TBAB:TBAC (*left*) and TBAB:TBAI (*right*) mixtures. Conditions: see Tab. 1.

Hydroxycarbonylation of styrene was studied at different CO pressures, temperatures and compositions of catalytic system. The reaction yields hydratropic (**1**) and hydrocynnamic (**2**) acids. Also ethylbenzene (**3**) was found in the reaction mixture at appropriate conditions.



1 **2**

Both styrene conversion and acids yield depend on pressure in a nearly linear fashion. Only a trace amount of **3** was detected among the products. At a pressure below 1.5 MPa, the major product was linear acid **2**; with an increase in the pressure, the **1**/**2** ratio growth (Tab. 2). Similar effect was found by others [7, 9, 26] for styrene carbonylation in common solvents and may be attributed to increased acidity of Pd species when PPh_3 is replaced by strong π-acceptor ligand such as CO. Also CO replacing PPh_3 at elevated pressure renders Pd complex less bulky also favours formation of linear acid **1**.

Table 2. Effect of CO pressure on styrene hydroxycarbonylation [a]

P, MPa	Conversion, %	Yield **1** + **2** (GLC)	**1**/**2** ratio
1.0	46	37	0.3
1.5	52	48	0.5
2.0	57	49	1.1
5.0	91	78	2.1
7.0	98	91	2.7

[a] 4 mmol styrene, 0.02 mmol $PdCl_2(PPh_3)_2$, 1.6 mmol HCl, 20 mmol H_2O, 1 g TBAB, 5 mL heptane. T 110°C, 2 h.

Enhancing temperature accelerates the reaction. However, the effects are not linear. Up to a temperature of 120 °C, the yield of the acids and the styrene conversion increased in a parallel manner, styrene being insignificantly hydrogenated into ethylbenzene. With a further increase in the temperature, the yield of ethylbenzene increased dramatically, with a respective decrease in the acid yields. At 150 °C, the conversion of the substrate was complete and the yields of the acids and ethylbenzene were 43 and 36%, respectively (Fig. 3). Palladium black formation was observed when T > 120°C. The **1**/**2** ratio was also temperature dependent. Selectivity to **1** decreased with temperature increase up to 130°C, which corresponds the literature data [7] However, further increase in the temperature caused reverse order in the selectivity (Fig. 4). Above observations suggest that the nature of the catalyst changes at T>120°C. Apparently, metallic Pd forming at high temperature catalyses styrene hydrogenation into **3** and probably carbonylation, too.

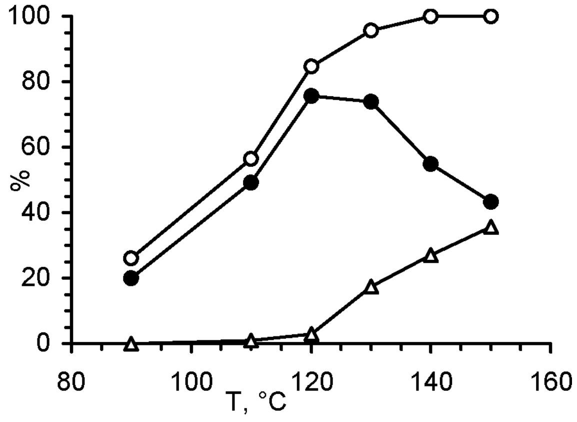


Fig. 3. Effect of the temperature on styrene conversion (empty rounds), acids yield (filled rounds) and ethylbenzene yield (triangles)

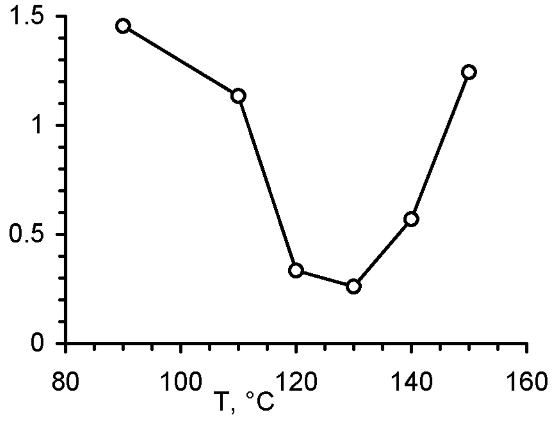


Fig. 4. Effect of the temperature on the **1**/**2** ratio.

Tab. 3 contains representative results on styrene hydroxycarbonylation in different IL media. In TBAB, $Pd(OAc)_2$ was more active than $PdCl_2(PPh_3)_2$. A reverse order was found in the TBAC. The selectivity to **1** was higher in TBAC regardless the presence of PPh_3. The same effect of the anion nature was found in [BMIM]-containing ILs. Namely, replacing bromide by chloride increased the activity of the phosphine-containing catalyst and greatly enhanced the selectivity to the branched acid. The phosphine-free palladium catalyst was more active but less selective to **1** than $PdCl_2(PPh_3)_2$ in the [BMIM][Br] medium.

Table 3. Hydroxycarbonylation of styrene [a]

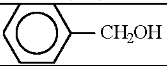
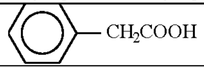
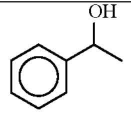
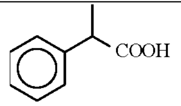
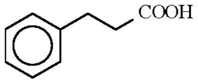
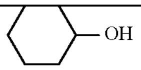
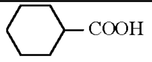
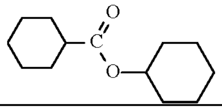
Catalyst	Ionic liquid	Conversion, %	Acids yield, %	**1**/**2** ratio
$Pd(OAc)_2$	TBAB	97	87	0.8
–"– [b]	–"–	94	83	1.0
–"–	TBAC	22	16	6.3
–"–	[BMIM][Br]	61	52	0.4
$PdCl_2(PPh_3)_2$	TBAB	33	29	1.0
–"– [b]	–"–	76	69	1.4
–"–	TBAC	100	90	7.2
–"–	[BMIM][Br]	13	10	1.0
–"–	[BMIM][Cl]	26	22	10.4

[a] 4 mmol styrene, 0.02 mmol [Pd], 0.08 mmol $TsOH·H_2O$, 20 mmol H_2O, 2 g IL, 5 mL heptane. T 110°C, P 5 MPa, 2 h. [b] HCl as an acidic promoter.

Hydroxycarbonylation of alcohols

Primary and secondary alcohols, aliphatic and 1-phenyl-substituted alcohols undergo hydroxycarbonylation in TBAB media in the presence of $Pd(OAc)_2$ as a catalyst precursor. The reactions with methanol, 1-phenylethanol and benzyl alcohol occur smoothly to give carboxylic acids in moderate to high yields. The carbonylation of n-butanol gives butyl valerate in 66% yield. The conversion of cyclohexanol was as small as 13% over 2 h; in this case, almost equal amounts of cyclohexanecarboxylic acid and its ester were formed. Water added to the starting mixture did not increase the yield (Tab. 4).

Table 4. Hydroxycarbonylation of alcohols in TBAB medium [a]

Alcohol	Conversion, %	Product	Yield, % (GLC)
CH_3OH	73	CH_3COOH	65
C_2H_5OH	32	C_2H_5COOH $C_2H_5COOC_2H_5$	19 9
н-C_4H_9OH	73	$C_4H_9COOC_4H_9$	66
	98		87
	100	 **(1)**  **(2)**	43.5 44
	13	 	6 5

[a] 4 mmol alcohol, 0.02 mmol $Pd(OAc)_2$, 0.08 mmol $TsOH\cdot H_2O$, 2 g TBAB, T 110°C, P 5 MPa, 2 h.

In hydroxycarbonylation of 1-phenylethanol (PE) both **1** and **2** were formed. Styrene also may be found in the reaction mixture and possibly to be one of the intermediates [12, 13]. In $Pd(OAc)_2$–TsOH–TBAB catalytic system the total yield of acids was almost independent of the carbon monoxide pressure in the range of 10–50 bar. A pressure lower than 10 bar is obviously insufficient for hydroxycarbonylation. Styrene was formed predominantly. (Fig. 5).

The higher the pressure, the higher the **1**/**2** molar ratio (Fig. 6). This result agrees with known data on higher regioselectivity to branched acid at elevated pressure in the carbonylation of 1-(4-isobutylphenyl)ethanol [12].

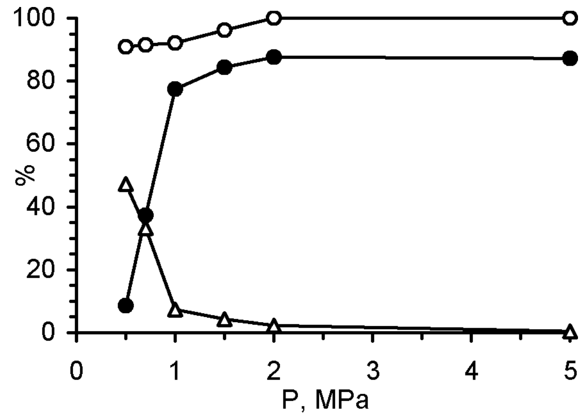


Fig. 5. Effect of the pressure on conversion (empty rounds), acids yield (filled rounds) and styrene yield (triangles)

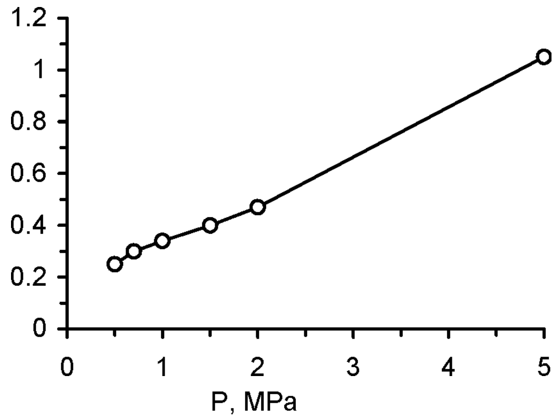


Fig. 6. Effect of the pressure on the **1**/**2** ratio.

The acids yield and reaction selectivity strongly depend on both the molten salt nature and the catalyst composition. The phosphine-free catalysts seemed to be very active in TBAB and [BMIM][Br] media in the presence of strong acids as a promoter. ILs containing Cl^-, BF_4^- and PF_6^- anions are unsuitable media for PE hydroxycarbonylation. Remarkably, dehydratation of PE occured in [BMIM][BF_4] and [BMIM][PF_6] media but not in TBAC and [BMIM][Cl]. The highest regioselectivity to **1** was reached in Cl^--containing ILs (Tab. 5).

Table 5. Hydroxycarbonylation of 1-phenylethanol [a]

Catalyst	Ionic liquid	Acid yield, % (GLC)	**1**/**2** ratio	Styrene yield, % (GLC)
$Pd(OAc)_2$	TBAB	81	1.1	0.4
–“– [b]	–“–	87	1.0	0.2
–“– [c]	–“–	56	1.7	19.5
–“– [d]	–“–	82	1.4	7
–“–	TBAC	tr.	–	4
–“–	[BMIM][Br]	86	0.4	0
–“–	[BMIM][Cl]	4	0.3	0.1
–“–	[BMIM][BF_4]	tr.	–	35 [e]
–“–	[BMIM][PF_6]	tr.	–	13 [e]
$PdCl_2(PhCN)_2$	TBAB	85	2.2	1
$PdCl_2(Py)_2$	–“–	77	2.2	2
$PdCl_2(PPh_3)_2$	–“–	42	2.5	36
–“–	TBAC	18	16.9	0
–“– [f]	–“–	45	12.9	0
–“–	[BMIM][Br]	8	0.7	57
–“–	[BMIM][Cl]	7	9.8	4
$Pd(PPh_3)_4$	TBAC	16	16.7	0

[a] Run conditions: 4 mmol 1-phenylethanol, 0.02 mmol catalyst, 0.8 mmol $TsOH{\cdot}H_2O$, 2 g ionic liquid; T 110°C, P 50 bar. 2 h. [b] 20 mmol H_2O were added. [c] 5 mL heptane were added. [d] HBr as an acidic promoter instead of TsOH. [e] Polymers were found in the reaction products. [f] Run time 4 h.

The general shape of the the time-concentration curves points styrene as principal reaction intermediate. Similar curves were obtained in [12]. However, the **1**/**2** ratio decreased from 7 in the first 30-min run to ~1.7 in 80 min. This fact contradicts the consecutive scheme PE → styrene → **1**+**2**. It is more likely that the two mechanisms operate simultaneously.

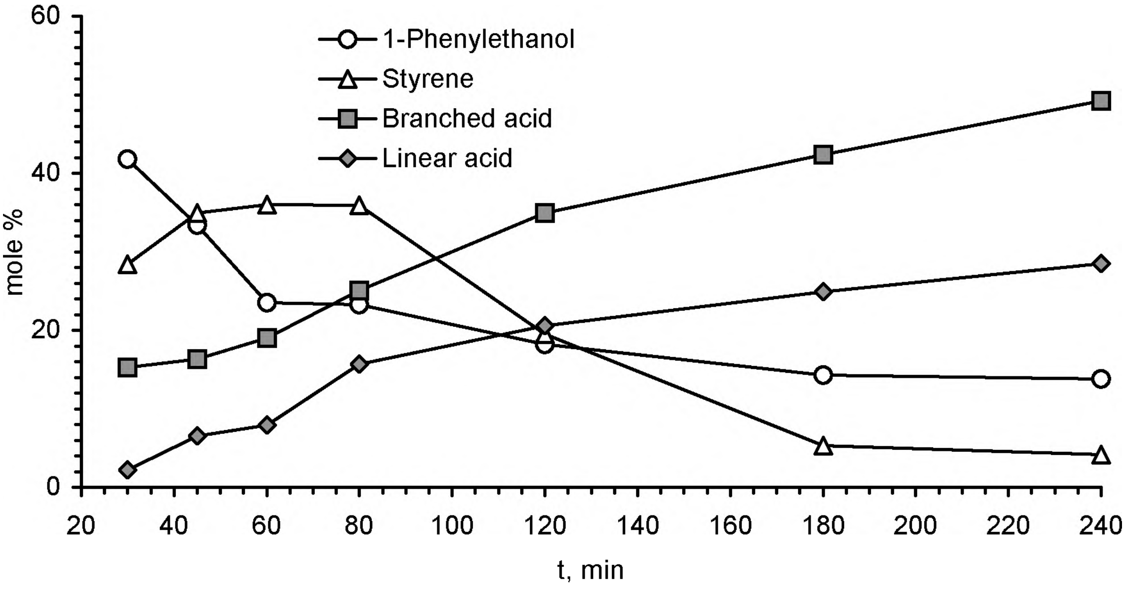


Fig. 6. Time-concentration curves in PE hydroxycarbonylation. Conditions: see Tab. 5, line 3.

Based on observed regularities in PE and styrene hydroxycarbonylation (Tab. 3, 5) we assume that at least two reaction pathways are involved (Fig. 7).

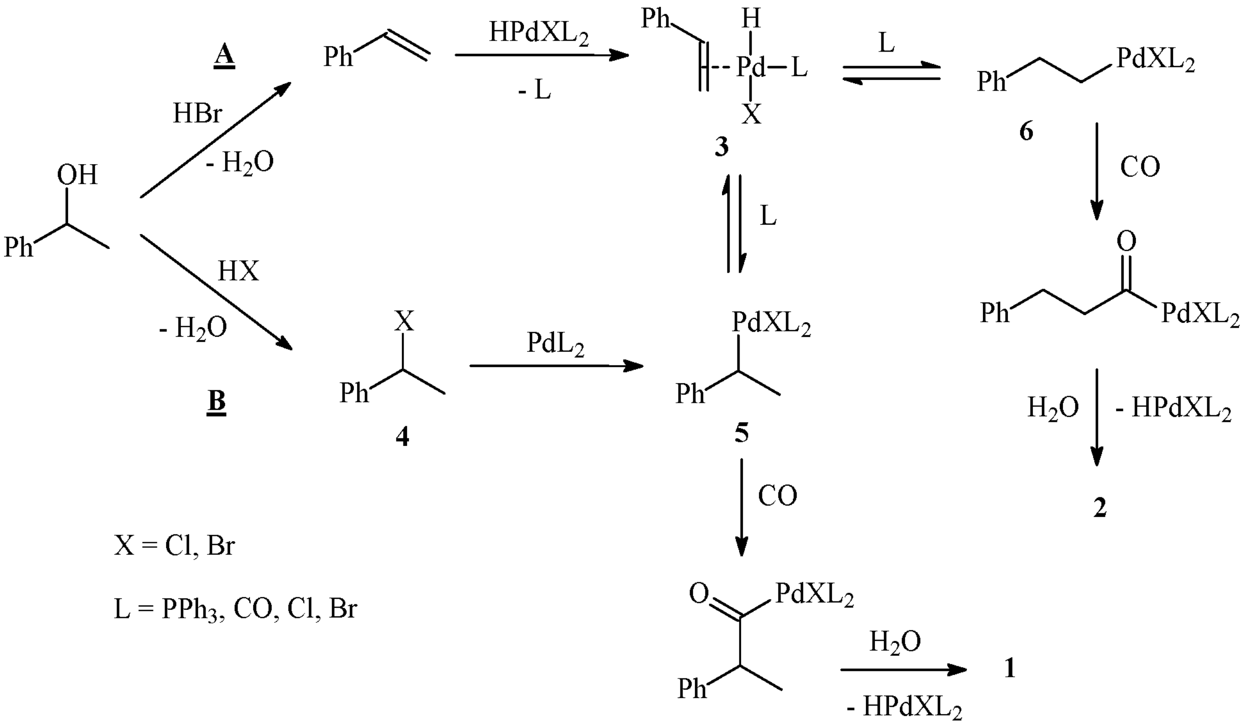


Fig. 7. Proposed scheme of 1-phenylethanol hydroxycarbonylation.

An important advantage of ILs is a simple procedure for catalyst recovering. The products are generally weakly soluble in the IL and may be simply separated from the catalyst. We used extraction with ether followed by decantation of ether layer. The catalyst remained in the TBAB and could be used repeatedly upon adding a new portion of PE. However, the acid promoter was partly extracted too, so that we had to add it in every run. To prevent gradual replacement of Br^- by another anion (this is essential for catalyst activity, see Tab. 3, 5) we used HBr as the acidic promoter. As a result, $Pd(OAc)_2$–HBr–TBAB catalytic system maintains the initial activity and selectivity for at least nine runs (Fig. 8). Notably, all reloading operations were carried out in air.

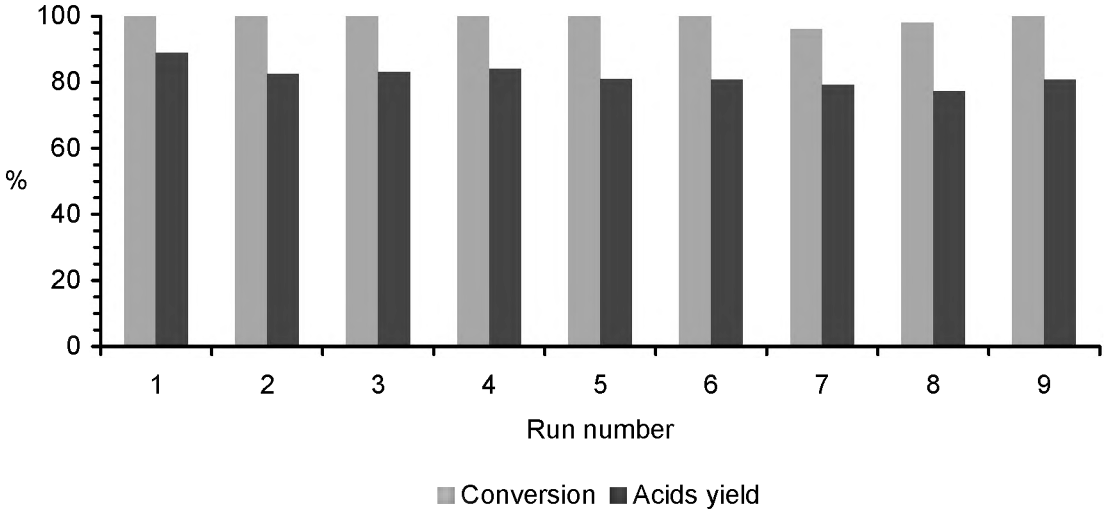


Fig. 8. Catalyst recycling. Conditions: 4 mmol PE, 0.02 mmol $Pd(OAc)_2$, 0.08 mmol HBr, 2 g TBAB, T 110°C, P 5 MPa, 2 h.

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