Hydroesterification of styrene using an in situ formed Pd(OTs)$_2$(PPh$_3$)$_2$ complex catalyst

A. Seayad [a], A.A. Kelkar [a], L. Toniolo [b], R.V. Chaudhari [a, *]

[a] *Homogenous Catalysis Division, National Chemical Laboratory, Pune 411008, India*
[b] *Departmento di Chimica, Universita di Venezia, Calle Large-S, Marta 2137-30123, Venice, Italy*

Abstract

Hydroesterification of styrene to 3-phenyl propionate **1**, and 2-phenyl propionate **2**, has been studied using a Pd(OTs)$_2$(PPh$_3$)$_2$ catalyst formed in situ from Pd(OAc)$_2$, PPh$_3$ and *p*-toluenesulfonic acid (*p*-tsa). Because of the weakly coordinating properties of the TsO$^-$ ligand, the catalyst has vacant coordination sites capable of easy activation of reactants. The presence of water is found to be necessary for the reaction and hydrogen enhances the catalytic activity under certain conditions (with Pd: *p*-tsa = 1). The beneficial effect of hydrogen, *p*-tsa and water is discussed in terms of favoring the formation of a Pd–H species, which initiates the catalytic cycle through the insertion of styrene into this bond with formation of a Pd-alkyl intermediate, which inserts CO to give a Pd-acyl intermediate, which, upon nucleophilic attack of the alkanol on the carbon atom of the acyl ligand, yields the final product and the starting hydride back to the catalytic cycle. *p*-tsa would favor the formation of a Pd–H species by reactivating any Pd(0) species that may form during the course of catalysis. Water would favor the formation of a Pd–H species through a reaction closely related to the water–gas shift reaction. The effect of various ligands, promoters, solvents and alcohols on catalytic activity as well as selectivity pattern has been studied. Regioselectivity to the branched product, **2**, increases with decrease in basicity of the phosphorous ligands as well as steric bulk around the palladium center and polarity of the medium. © 2000 Elsevier Science B.V. All rights reserved.
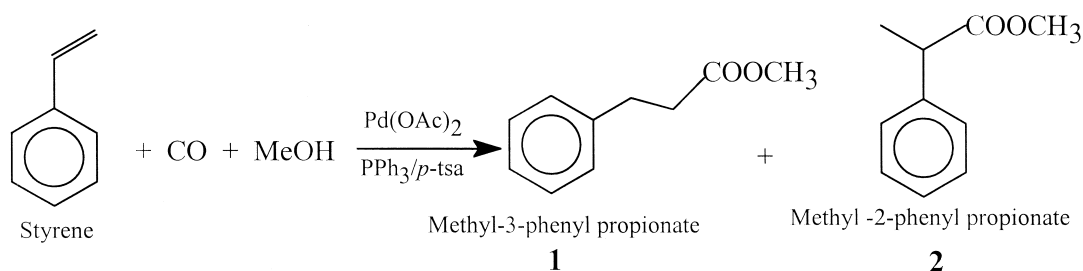
Keywords: Hydroesterification; Carbonylation; Styrene; Palladium; Activity; Regioselectivity; Arylpropionic acid

1. Introduction

Transition metal catalysed hydroesterification of vinyl aromatics are gaining importance for the synthesis of industrially valuable products such as 2-phenylpropionic acids/esters, a class of non-steroidal anti-inflammatory agents [1–3].

A variety of soluble palladium complexes are widely used due to their high activity and selectivity [4–8]. Branched as well as linear carboxylic acid esters are formed in these reactions and the regioselectivity is strongly dependent on the catalytic system employed and the reaction conditions used [9–13]. The alkoxycarbonylation of styrene, one of the simplest examples of vinyl aromatics, yields a mixture of 2-phenyl propionate (branched product, **2**) and 3-phenyl propionate (linear product, **1**), as given below in Scheme 1 using methanol as the alkanol.

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* Corresponding author. Tel.: +91-20-5893260; fax: +91-20-5893260; E-mail: rvc@ems.ncl.res.in

Scheme 1. Hydroesterification of styrene.

Alkoxycarbonylation (hydroesterification) of styrene with neutral palladium complexes such as PdCl$_2$(PPh$_3$)$_2$, PdCl$_2$(dppp)$_2$ (dppp = diphenylphosphino propane) was reported to proceed under severe conditions (200–700 atm of CO) and the activity was found to be rather low [14–16]. Under these conditions regioselective formation of **2** was observed with monophoshines [14] as ligands and that of **1** was observed with diphos ligands [15,16]. Increased regioselectivity to **2** was reported with Pd(OAc)$_2$ immobilised on montmorillonite in the presence of HCl as a promoter [17] under milder conditions of 25°C and 600 psig of carbon monoxide. A similar homogeneous catalytic system [18], comprising of Pd(OAc)$_2$ and diphenylphosphinoacetic acid along with p-toluenesulfonic acid (p-tsa) as an auxiliary component, was reported to have a drastic decreasing effect on the regioselectivity to **2**. In recent developments, cationic palladium complexes with improved catalytic activity at milder reaction conditions have been reported [19,20]. Oi et al. [19] have reported hydroesterification of styrene using a cationic palladium complex, [Pd(PhCN)$_2$(PPh$_3$)$_2$](BF$_4$)$_2$, with a TOF of 11 h^{-1} and a n/iso ratio of 1.5. Another cationic palladium complex generated in situ [19,20] from Pd(OAc)$_2$, PPh$_3$ and p-tsa gave enhanced selectivity towards **2** (95%) at room temperature. The weakly coordinating property of the TsO$^-$ anion is believed to facilitate activation of substrate molecules. In a recent paper of ours [20] on the kinetics of carboxylation of styrene using this catalytic system, it was reported that water enhances the catalytic activity due to the increased formation of Pd–H in the presence of water and the catalytic cycle starts from the initial insertion of styrene into a Pd–H bond. In this paper, the effect of various parameters such as type of ligands, ligand to metal ratio, anion to catalyst ratio, solvents and the effect of hydrogen at different temperatures on the catalytic activity and product selectivity is reported.

2. Experimental section

2.1. Materials

Styrene and 4-substituted styrenes, Pd(OAc)$_2$, PdCl$_2$, PPh$_3$, P(p-tol)$_3$, P(o-tol)$_3$, P(Bu)$_3$, P(p-ClC$_6$H$_4$)$_3$, P(OPh)$_3$, P(MeOC$_6$H$_4$)$_3$, p-toluenesulfonic acid monohydrate, methanesulfonic acid, trifluoroacetic acid, triflic acid (all from Aldrich, USA), and CO (Matheson, USA) were used as received without further purification. Methanol was distilled and dried using known procedures before use. Other solvents and alcohols were also distilled before use.

2.2. General procedure

Liquid samples were analysed on a HEWLETT PACKARD 690 Series GC, which is controlled by the HP Chemstation software, by using an FFAP megabore column (30 m × 0.53 mm × 0.1 μm film thickness, on a poly(ethyleneglycol) stationary phase). IR was obtained from a SHIMADZU HYPER IR in

DRS (Diffused Reflectance Spectroscopy) mode by mixing samples with KBr.

All reactions were carried out in a 50 ml Parr Autoclave made of Hastelloy-C276 having facilities for gas inlet, outlet, intermediate sampling, temperature controlled heating and variable agitation speed (for schematic of the reactor set-up, see Ref. No. [20]). In a typical experiment, $Pd(OAc)_2$ (0.06 mmol), PPh_3 (0.24 mmol), p-tsa (0.6 mmol) and styrene (14.42 mmol) were dissolved in methanol (23.3 ml) to make the total volume 25 ml and charged to the reactor. The reactor was purged first with nitrogen and subsequently with carbon monoxide at room temperature and the contents heated to 75°C. After attaining the temperature, the reactor was pressurised to 500 psig with CO and the reaction was started at 900 rpm. The reaction was carried out at a constant pressure by feeding CO from a reservoir. The progress of the reaction was monitored by measuring the absorption of CO in the reservoir as a function of time. The reaction was carried out for one hour at the end of which the liquid phase was quantitatively analysed for reactant and products. The mass balance of CO absorbed and styrene consumed, and the products formed was found to be more than 97% based on the stoichiometry [20].

2.3. Preparation of $Pd(OAc)_2(PPh_3)_2$

The literature procedure [21] was followed with very little modification. $Pd(OAc)_2$ (0.116 mmol) and PPh_3 (0.235 mmol) were dissolved in toluene with vigorous shaking. To the resulting yellow solution, n-hexane was added and the precipitated yellow $Pd(OAc)_2(PPh_3)_2$ complex was filtered, washed with n-hexane and dried under vacuum. Yield: 62%; IR: 1633 (ν, C $=$ O) cm^{-1}, 1350 (δ, C–O) cm^{-1}.

2.4. Preparation of $Pd(OTs)_2(PPh_3)_2$, (I)

The above complex, $Pd(OAc)_2(PPh_3)_2$, was dissolved in toluene and two equivalents of p-tsa was added with vigorous shaking in a

Schlenk flask under argon atmosphere. Immediate precipitation with n-hexane gave a yellowish complex, which was allowed to settle down. The supernatant liquid was decanted [1] and the complex was washed several times with n-hexane and finally with a little of ether and taken to dryness under vacuum. Complex **I** is only moderately stable in air. IR: 1036 (ν, SO_3) cm^{-1}. Anal. Calcd for $C_{50}H_{44}O_6P_2PdS_2$: C, 61.6; H, 4.55; S, 6.58. Found: C, 59.92; H, 5.01; S, 6.37. Complex **I** was also formed when a mixture of $Pd(OAc)_2$, PPh_3, and p-tsa was used instead of $Pd(OAc)_2(PPh_3)_2$ as the precursor.

3. Results and discussion

3.1. Effect of catalyst and reaction parameters

3.1.1. Catalyst system

The catalytic system used in this work is a mixture of $Pd(OAc)_2/PPh_3/p$-tsa, in the ratio of $1/4/10$ unless otherwise stated, from which the active catalyst species is formed in situ. This catalyst system shows similar activity as that of $Pd(OAc)_2(PPh_3)_2$ or $Pd(OTs)_2(PPh_3)_2$ (Table 1). This is because $Pd(OAc)_2$ reacts with PPh_3 immediately forming an yellow complex, $Pd(OAc)_2PPh_3$ [22,23], which, is converted to $Pd(OTs)_2(PPh_3)_2$, **I**, on subsequent reaction with p-toluenesulfonic acid (see Section 2).

$$Pd(OAc)_2 + 2PPh_3 + 2TsOH$$

$$\rightarrow \underset{\text{(I)}}{Pd(OTs)_2(PPh_3)_2} + 2AcOH \qquad (1)$$
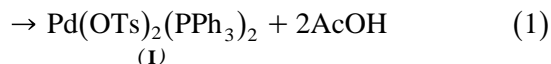
Complex **I** is only moderately stable in air and changes to a brown coloured complex slowly on storage. This catalytic system is significantly more active than the neutral precursor such as $PdCl_2(PPh_3)_2$. This is probably due to

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[1] Decantation was used because, on filtration, the majority of the yellow complex, **I**, changed to a reddish brown (sticky mass) even under argon atmosphere, but stable at low temperatures.

Table 1

Effect of catalyst precursors in the hydroesterification of styrene

Reaction conditions. Styrene: 14.5 mmol, Catalyst: 0.06 mmol, *p*-tsa: 0.6 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

Sr. no.	Catalyst	Conversion %	Selectivity %, (yield, %)		n/iso ratio	TOF h^{-1}
			iso-ester	*n*-ester		
1	Pd(OAc)$_2^a$	84.2	39.8 (33.5)	60.2 (50.6)	1.51	203
2	Pd(OAc)$_2$(PPh$_3$)$_2^b$	85.0	40.0 (34)	59.8 (50.8)	1.49	205
3	Pd(OTs)$_2$(PPh$_3$)$_2^{b,c}$	99.8	40.7 (40.6)	59.2 (59.4)	1.45	248
4	Pd(PPh$_3$)$_4^d$	96.0	38.6 (37.1)	61.3 (58.8)	1.59	234

^{a}PPh$_3$: 0.24 mmol, ^{b}PPh$_3$: 0.12 mmol, ^{c}*p*-tsa: 0.48 mmol, ^{d}no added PPh$_3$.

the fact that in the present system there is in situ formation of Pd(OTs)$_2$(PPh$_3$) in which the charge of the central metal cation is balanced by weakly coordinating anions TsO$^-$ so that the cation is left with free co-ordination sites able to activate the reactant molecules more effectively compared to the other system, in which the charge of the central metal cation is balanced by strongly coordinating anion Cl$^-$. A comparison of the catalytic activity and selectivity of the in situ formed and preformed catalytic precursors are given in Table 1. Similar catalytic activity and selectivity is observed in all cases.

3.1.2. Effect of ligands

The effect of the different phosphorous ligands used is summarised in Table 2. The activity is found to increase in the order P(*p*-MeOC$_6$H$_4$)$_3$ < P(*p*-ClC$_6$H$_4$)$_3$ < P(*p*-tol)$_3$ < P-(*m*-tol)$_3$ < PPh$_3$. No reaction is observed in the case of PCy$_3$, PBu$_3$ and P(OPh)$_3$. In the last case, complete precipitation of palladium metal is observed, unlike the experiments with PCy$_3$ and PBu$_3$ in which the solution is light yellow in colour, which indicates formation of some stable complexes. Phosphines having no substituents in the benzene ring (PPh$_3$) gave the highest activity (TOF = 203 h^{-1}). This may be related to the modified ability of the metal to coordinate styrene and carbon monoxide. For example, with more basic ligands, coordination of styrene, because of its nucleophilic character, would be disfavored, while with less basic ligands, styrene would bind too strongly. In addition styrene migration to coordinated CO (see later) can be also affected by the different electronic properties of the ligands. Thus, apparently PPh$_3$ gives the best compromise with respect to the catalytic activity.

The product selectivity is also affected drastically by the nature of the ligand. The n/iso ratio is the lowest ($n/iso = 0.44$) with P(*p*-

Table 2

Effect of ligands in the hydroesterification of styrene

Reaction conditions. Styrene: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, Ligand: 0.24 mmol, *p*-tsa: 0.6 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

Sr. no.	Ligand	Conversion %	Selectivity %, (yield %)		n/iso ratio	TOF h^{-1}
			iso-ester	*n*-ester		
1	PPh$_3$	84.2	39.8 (33.4)	60.2 (50.5)	1.51	203
2	P(*p*-tol)$_3$	39.8	25.7 (10.2)	73.6 (29.3)	2.86	83
3	P(*m*-tol)$_3$	39.0	29.0 (11.3)	71.0 (27.7)	2.44	78
4	P(*p*-MeOC$_6$H$_4$)$_3$	10.6	20.5 (2.2)	79.4 (8.4)	3.86	26
5	P(*p*-ClC$_6$H$_4$)$_3$	20.5	69.2 (14.1)	30.7 (6.29)	0.44	49

Table 3
Effect of PPh_3/Pd ratio in the hydroesterification of styrene
Reaction conditions. Styrene: 14.5 mmol, $Pd(OAc)_2$: 0.06 mmol, p-tsa: 0.6 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

| Sr. no. | PPh_3/Pd ratio | Conversion % | Selectivity %, (yield %) | | n/iso ratio | TOF h^{-1} |
			iso-ester	n-ester		
1	2	81.0	44.0 (35.6)	55.8 (45.2)	1.27	197
2	4	84.2	39.8 (33.5)	60.2 (50.6)	1.51	203
3	6	64.9	37.4 (24.2)	60.6 (39.3)	1.62	153
4	10	55.5	36.5 (20.2)	62.4 (34.6)	1.71	132

$ClC_6H_4)_3$ and found to increase with increase in basicity of the ligand (see Table 2). This indicates that the ligand plays an important role in the regioselectivity-determining step, which is proposed to be the transition from a π-olefin complex **B** to σ-alkyl complexes **D** or **E** (Scheme 2). When the π-complex **B** changes to σ-alkyl complex after the insertion of styrene into the Pd–H bond, the styrene moiety can adopt either iso, **D**, or linear, **E**, type co-ordination depending on the steric and electronic factors. It is also proposed that these species can interconvert through a π-benzylic [24,25] type species **C**. Since the ligands differ little for their steric hindrance, the observed trend in selectivity can be mainly ascribed to electronic factors.

It is interesting to note that using the most basic ligand $P(p\text{-OMeC}_6H_4)_3$, or the less basic one, $P(p\text{-ClC}_6H_4)_3$, the yield in n-ester is not much different (8.4% and 6.29%, respectively) while the yield in iso-ester is ca. 7 times higher when employing the less basic ligand (Table 2).

Electron withdrawing substituents in the phenyl group renders the phosphorus atom a poor σ-donor and a good π-acceptor [26], which decreases the electron density of the palladium center. This favors the formation of **D** thereby increasing the formation of **2**.

3.1.3. Effect of PPh_3/Pd ratio

The ratio of PPh_3/Pd is also found to have a significant role in catalyst activity and product
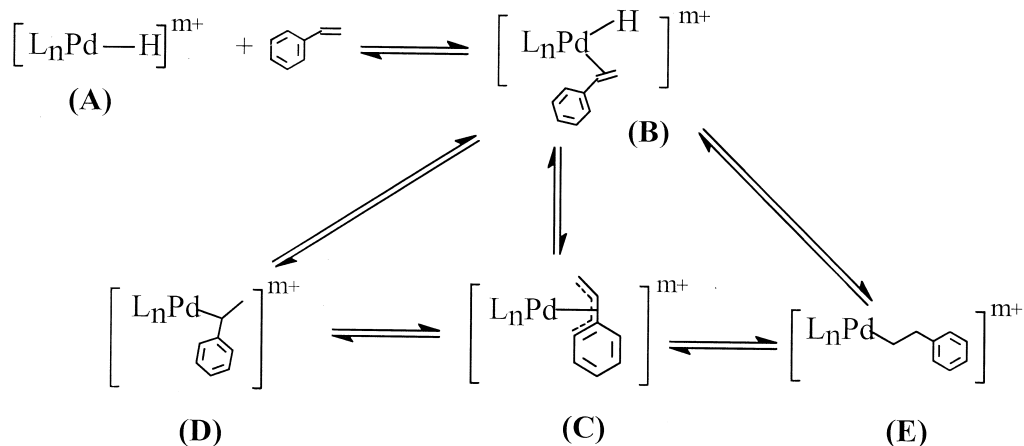
$L = PPh_3, TsO^-, CO$ or solvent; $n = 2, 3$ or 4; $m = 0$ or 1

Scheme 2.

selectivity (Table 3). No catalytic activity is observed without phosphorous ligands and complete precipitation of palladium metal results under experimental conditions. The catalytic activity increases up to a PPh_3/Pd ratio of four, and decreases steadily with further increase. With a PPh_3/Pd ratio of two, substantial precipitation of the active catalyst to Pd metal is observed and no metal precipitation is observed above a ratio of four. With increase in PPh_3/Pd ratio, PPh_3 competes with the reactant molecules for co-ordination, causing decrease in the activity.

A gradual increase in the n/iso ratio is observed with increase in PPh_3/Pd ratio. With increase in the concentration of PPh_3, it is likely that the palladium center can have more than one PPh_3, which can increase the steric as well as electronic density at the palladium center so that the equilibrium of Scheme 2 will be shifted

towards **E**, resulting the increased formation of the linear product, **1**.

3.1.4. Effect of p-toluenesulfonic acid concentration

The presence of *p*-tsa is necessary to form the catalytically active cationic species as without *p*-tsa the reaction does not occur and $Pd(OAc)_2(PPh_3)_2$ complex is isolated from the final reaction mixture. Effect of the concentration of *p*-tsa on catalytic activity is shown in Fig. 1.

The catalytic activity is considerably low (TOF of 11 h^{-1}) with one equivalent of *p*-tsa but a sudden jump in TOF (159 h^{-1}) is observed as the ratio is increased to 2.5, which is in slight excess of the quantity required to form $Pd(OTs)_2(PPh_3)_2$. The TOF is found to increase up to a ratio of 10 and remained almost constant (TOF = 203 h^{-1}) with further increase. It is
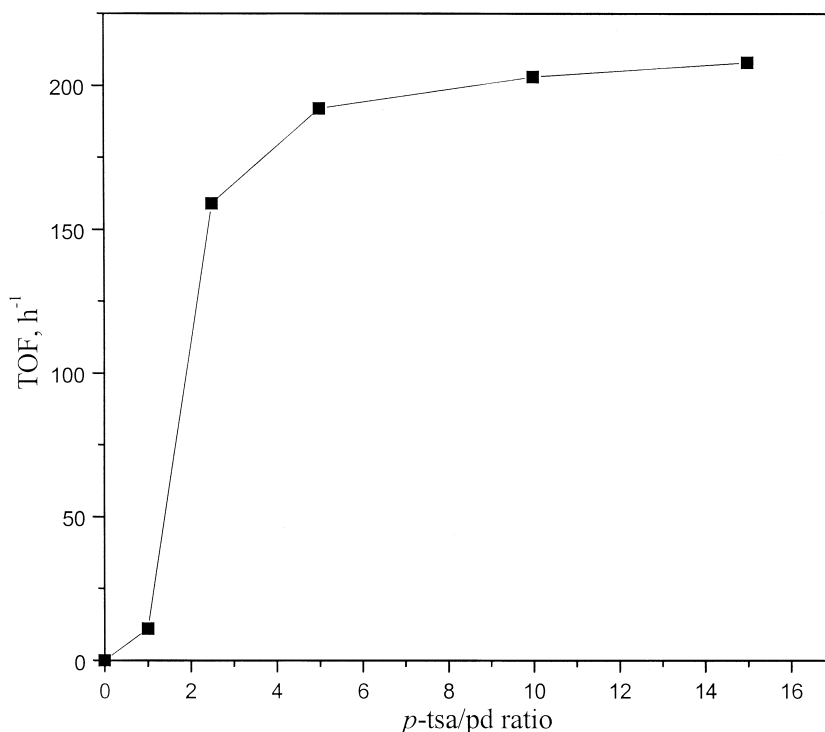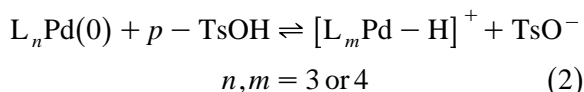

Fig. 1. Effect of *p*-tsa concentration. Styrene: 14.5 mmol, $Pd(OAc)_2$: 0.06 mmol, PPh_3: 0.24 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

also likely that *p*-tsa plays an important role in the reactivation of any Pd(0) that may form during the course of catalysis by regenerating the active Pd–H species:

$$L_nPd(0) + p-TsOH \rightleftharpoons [L_mPd-H]^+ + TsO^-$$

$$n, m = 3 \text{ or } 4 \qquad (2)$$

In addition, at lower concentrations of *p*-tsa and in the presence of excess methanol the palladium precursor can form an inactive or less active palladium carbomethoxy [27,28] complex:

$$[L_nPd(CO)]^{x+} + MeOH$$

$$\rightleftharpoons [L_nPd(COOMe)]^{x+} + H^+$$

$$x = 0, 1 \text{ or } 2 \qquad (3)$$
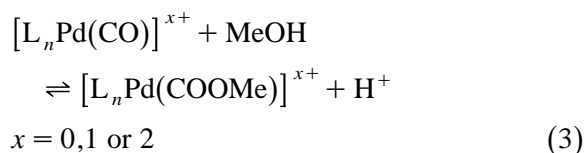
Selectivity is not affected by change in *p*-tsa concentration, which suggests that OTs^- may not be very strongly coordinated to the Pd center.

3.1.5. Effect of different acidic promoters

The effect of different acidic promoters is given in Table 4. The activity decreases in the order *p*-tsa > msa > triflic acid > trifluoroacetic acid, which is in the reverse order of the coordination ability of the anion. Higher activity is observed with sulfonic acids and higher selectivity to *iso* product is obtained in the case of triflic acid.

In the presence of anions having higher binding abilities, availability of coordination sites around the central metal atom is reduced leading to a lower catalytic activity. Acetic acid [29] and oxalic acid [30], which are also used as promoters in hydrocarboxylation reactions, are found to be inactive under the present conditions. No precipitation of Pd metal is observed in these cases, but very faint yellow tinge of the final reaction mixture indicates the formation of stable complexes.

3.1.6. Effect of solvents

The effect of solvents is studied using methanol as a reactant (methanol/styrene = 5) and the results are presented in Table 5. Catalytic activity is found to be lower in less polar solvents like benzene and toluene, but increases with solvents having high polarity (methanol). A medium of low polarity favors the association between the complex cation and the counter ion, so that this competes with the reacting molecules for coordination. Coordinating solvents like methyl ethyl ketone and acetone decreased the catalytic activity due to the fact that the solvent, which assists the CO migration [31], can occupy the co-ordination sites. The reactivity pattern can also be affected by the concentration of CO in various solvents depending on the solubility [32–34]. In general, the activity increases with increase in dielectric constant of the reaction medium. Despite of the lower dielectric constant, catalytic activity is the highest when styrene is used as the solvent [20].

Table 4
Effect of different acidic promoters
Reaction conditions. Styrene: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, PPh$_3$: 0.24 mmol, acidic promoter: 0.6 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

Sr. no.	Acidic promoter	Conversion %	Selectivity %, (yield %)		*n/iso* ratio	TOF h^{-1}
			iso-ester	*n*-ester		
1	*p*-toluenesulfonic acid	84.2	39.8 (33.5)	60.2 (50.6)	1.51	203
2	methanesulfonic acid (msa)	61.6	41.1 (25.3)	58.8 (36.2)	1.43	148
3	triflouromethanesulfonic acid (triflic acid)	55.3	43.1 (23.8)	56.8 (31.4)	1.31	133
4	triflouroacetic acid	2.8	41.5 (1.1)	58.4 (1.6)	1.40	6.8

Table 5

Effect of solvents in the hydroesterification of styrene

Reaction conditions. Styrene: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, PPh$_3$: 0.24 mmol, p-tsa: 0.6 mmol, methanol: 72.5 mmol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

Sr. no.	Solvent	Conversion %	Selectivity %, (yield %)		n/iso ratio	TOF h^{-1}
			iso-ester	n-ester		
1	Benzene	39.75	69.8 (27.7)	30.0 (11.9)	0.429	95
2	Toluene	46.82	65.9 (30.8)	33.3 (15.6)	0.505	112
3	Methyl ethyl ketone	24.83	39.4 (9.7)	60.5 (15.0)	1.53	57.3
5	Acetone	9.55	30.8 (2.9)	69.1 (6.6)	2.25	23
6	Methanol	84.2	39.8 (33.5)	60.2 (50.6)	1.51	203
7	Styrene[a]	–	63.4	35.2	0.55	411

[a]See Ref. [20].

Polarity of the medium has a pronounced effect on the product selectivity as the n/iso ratio increases with increase in the polarity of the medium. The influence of polarity on the product selectivity can be clearly understood from the examples in which the solvents are methyl ethyl ketone (MEK) and acetone. Due to the steric hindrances associated with the coordinating solvents, it is also expected to have a higher n/iso ratio in MEK than acetone. However, lower n/iso ratio obtained for MEK compared to acetone indicates that the polarity of the medium is important in determining the selectivity.

3.1.7. Effect of different alcohols

The effect of different alcohols as esterification reagent is studied and the results are presented in Table 6. The catalytic activity decreased as the number of carbon atoms in the alcohol chain increased. According to the hydride mechanism, nucleophilic attack of the alcohol to the acyl complex is proposed to be the product forming step in the hydroesterification reactions of olefins [35,36]. The results reported in Table 6 suggest that with increase in carbon chain and increase in the bulkiness of alcohol, the rate of the nucleophilic attack decreases and hence the overall catalytic activity decreases. This is particularly evident by comparing the results with n-propanol and sec-propanol and n-butanol and sec-butanol. Moreover, the polarity of the medium can also affect the catalytic activity as observed for different solvents. Methanol, having highest polarity among the alcohols, gives highest activity.

With the exception of iso-propanol and sec-butanol, the n/iso ratio is found to decrease

Table 6

Effect of different alcohols in the hydroesterification of styrene

Reaction conditions. Styrene: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, PPh$_3$: 0.24 mmol, p-tsa: 0.6 mmol, alcohol: 72.5 mmol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

Sr. no.	Alcohol	Conversion %	Selectivity %, (yield, %)		n/iso ratio	TOF h^{-1}
			iso-ester	n-ester		
1	methanol	84.2	39.8 (33.5)	60.2 (50.6)	1.51	203
2	ethanol	56.2	40.7 (22.8)	59.1 (33.2)	1.47	135
3	n-propanol	40.7	44.2 (17.9)	55.7 (22.6)	1.25	97.6
4	iso-propanol	9.4	37.6 (3.5)	62.3 (5.8)	1.65	22.6
5	n-butanol	11.0	46.5 (5.1)	51.4 (5.6)	1.10	18.9
6	sec-butanol	3.7	32.3 (1.2)	67.1 (2.4)	2.67	8.7

from methanol to *n*-butanol. The decrease in polarity can be one of the reasons for the decreased *n/iso* ratio (see solvent effect above). In the case of *iso*-propanol and *sec*-butanol the decreased formation of branched product can be due to the steric factors.

3.1.8. Effect of methanol concentration

The effect of methanol concentration is studied in a non-coordinating and low polar solvent such as toluene. As shown in Fig. 2, at lower methanol concentrations (methanol/styrene = 2.5 to 10), the catalytic activity is found to increase linearly. Above a ratio of 10, the increase in TOF changed to some fractional order. Since the rate-limiting step in the hydroesterification reaction is proposed to be the nucleophilic attack of methanol on the acyl complex, the rate of reaction will be lower at lower concentration of methanol. Since the catalytic activity varies with a fractional order at higher methanol concentration, it is likely that a part of

the catalyst precursor is converted to some less active or inactive species such as carbomethoxy complex or that methanol competes for coordination.

The selectivity remains almost constant (*n/iso* ratio = 0.52) with increase in MeOH concentration up to a methanol to styrene ratio of 10. With further increase in the ratio, 10 to 35 (pure methanol), a steady increase in *n/iso* ratio (*n/iso* ratio = 0.94 and 1.51 at methanol/styrene ratio of 15 and 36 respectively) is observed. This trend clearly indicates that the product selectivity has a strong dependency on polarity of the medium, unlike the case of neutral complexes [35,36].

One interesting result obtained is that when methanol/styrene ratio reduced to 1.44 with excess of styrene, the TOF is found to increase ($284\ h^{-1}$) and the *n/iso* decreased to 0.97. On further decreasing the ratio to 0.8, a dramatic increase in reaction rate (TOF = $467.5\ h^{-1}$) is observed with a decreased *n/iso* ratio (0.52).

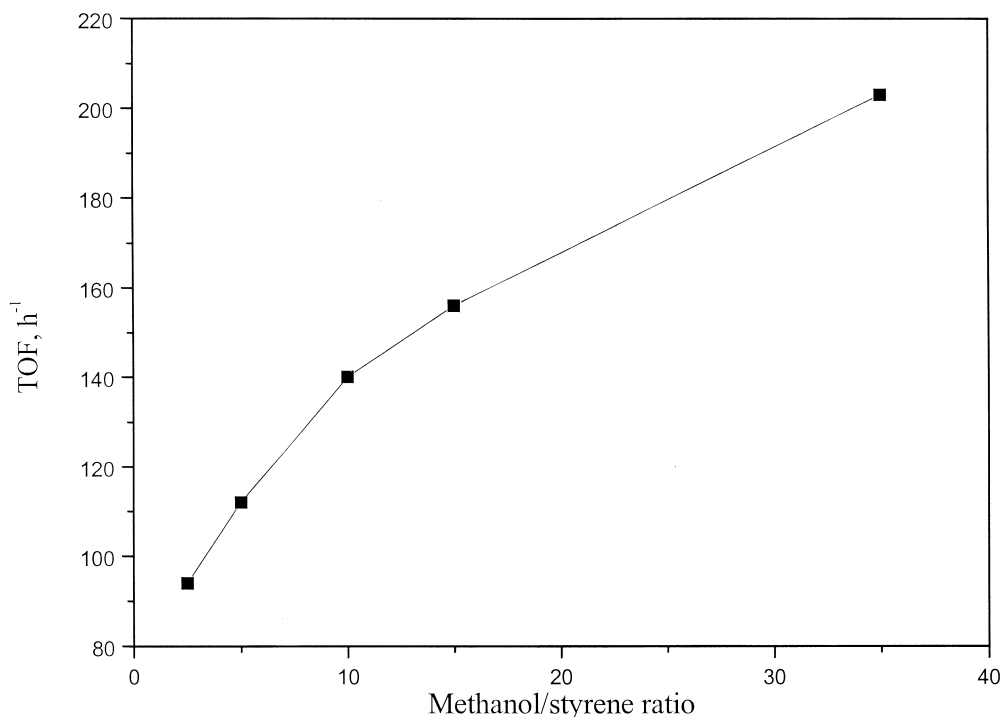Fig. 2. Effect of methanol concentration in toluene. Styrene: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, PPh$_3$: 0.24 mmol, *p*-tsa: 0.6 mmol, Solvent: toluene, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

3.1.9. Effect of hydrogen

Since palladium hydride is likely to be the active catalytic species in the hydroesterification of olefins [37], source and availability of the hydride species can have a significant effect on the catalytic activity. Hydrogen can be activated by a Pd(II) species according to the following equation:

$$[L_nPd]^+ + H_2 \rightleftharpoons [L_nPd-H]^+ + H^+ \qquad (4)$$
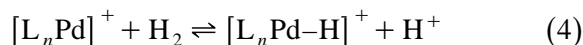
Only a very small increase in TOF (203 to 224 h^{-1}) is observed by the addition of 50 psig of hydrogen in the presence of 10 equivalent of *p*-tsa. On reducing the *p*-tsa concentration to one equivalent, a drastic decrease in TOF from 203 to 11 h^{-1} is observed and the catalytic activity increased suddenly with 50 psig of hydrogen (TOF, 113 h^{-1}) as shown in Fig. 3.

Since *p*-tsa can also act as a hydride source, the effect of hydrogen is more evident only at lower concentrations of the *p*-tsa. These obser-

vations suggest that the catalytic cycle proceed through a hydride mechanism. This kind of hydrogen effect was not observed for the hydroesterification of olefins using neutral complexes in methanol [35,36], which indicates the easy formation of methoxy complexes in methanol medium, while beneficial hydrogen effects were obtained in *n*-butanol that indicating the occurrence of the hydride mechanism. In presence of sufficient or excess of *p*-tsa formation of a carbomethoxy species will be suppressed (see Eq. (3)) and palladium hydride formation will be enhanced. The *n/iso* ratio remains almost unaffected (for a particular temperature) with change in hydrogen partial pressure.

3.1.10. Effect of substituents in styrene

Substrate effect is studied with different para substituted styrenes and the results are shown in Table 7. Either with electronegative or electropositive substituents the catalyst activity as well as *n/iso* ratio decreases.
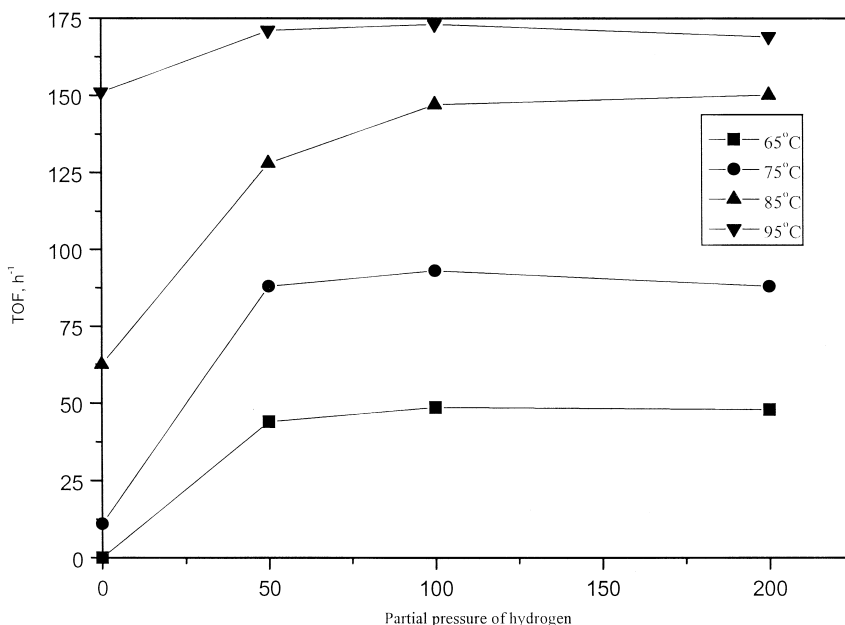

Fig. 3. Effect of hydrogen partial pressure. Styrene: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, PPh$_3$: 0.24 mmol, *p*-tsa: 0.06 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.
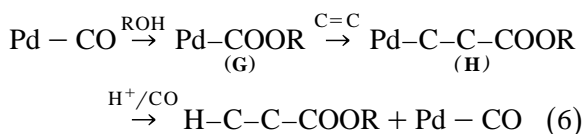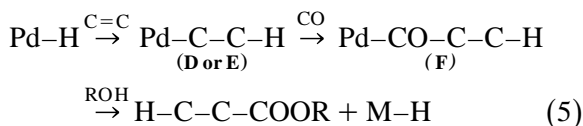
Table 7
Effect of 4-substituents in styrene
Reaction conditions. Substrate: 14.5 mmol, Pd(OAc)$_2$: 0.06 mmol, PPh$_3$: 0.24 mmol, p-tsa: 0.6 mmol, Solvent: methanol, Water: 2000 ppm, Reaction time: 1 h, Temperature: 348 K, P_{CO}: 3.4 MPa.

| Sr. no.	Substrate	Conversion %	Selectivity %, (yield %)		n/iso ratio	TOF h^{-1}
			iso-ester	n-ester		
1	styrene	84.2	39.8 (33.5)	60.2 (50.6)	1.51	203
2	4-methylstyrene	57.1	46.3 (26.4)	53.6 (30.6)	1.15	133
3	4-t-butylstyrene	36.5	47.4 (17.3)	52.4 (19.1)	1.10	88.2
4	4-chlorostyrene	37.5	52.5 (19.6)	47.4 (17.7)	0.90	104
5	4-acetoxystyrene	no reaction and Pd metal precipitation observed				

3.2. Reaction mechanism

Palladium catalysed hydroesterification of olefins is proposed to proceed through either a Pd–H [38,39] or Pd-COOR [40–43] as intermediates:

$$Pd-H \overset{C=C}{\rightarrow} \underset{(\textbf{D or E})}{Pd-C-C-H} \overset{CO}{\rightarrow} \underset{(\textbf{F})}{Pd-CO-C-C-H}$$

$$\overset{ROH}{\rightarrow} H-C-C-COOR + M-H \qquad (5)$$

$$Pd-CO \overset{ROH}{\rightarrow} \underset{(\textbf{G})}{Pd-COOR} \overset{C=C}{\rightarrow} \underset{(\textbf{H})}{Pd-C-C-COOR}$$

$$\overset{H^+/CO}{\rightarrow} H-C-C-COOR + Pd-CO \qquad (6)$$

Metal hydride mechanism (Eq. (5)) proceeds via insertion of CO to a Pd-alkyl species formed by the addition of olefin to the Pd–H bond and subsequent nucleophilic attack of ROH on the carbon atom of the acyl ligand. Alkoxy mechanism (Eq. (6)) involves the insertion of olefin into a metal carboalkoxy species, formed by the addition of ROH to initially formed metal carbonyl species. Carbonylation by using cationic complexes were also proposed to proceed through both the mechanisms [44,45]. The enhancement of reaction rate with water [20], p-tsa, and hydrogen suggests that the hydroesterification reaction is likely to proceed through a hydride mechanism. The beneficial effects of p-tsa and hydrogen have been discussed above. Water can increase the concentration of the palladium hydride species through interaction of CO with the formation of a species having Pd-(COOH) moiety, which upon elimination of CO$_2$ yields a Pd–H species.

$$[L_n Pd]^+ + CO + H_2O \underset{-H^+}{\rightarrow} [L_n Pd(COOH)]^+$$
$$\rightarrow [L_n Pd-H]^+ + CO_2 \qquad (7)$$
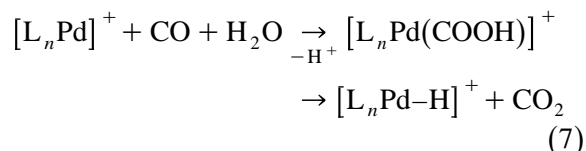
GC analysis showed traces of CO$_2$ and is confirmed by reaction with excess of catalyst precursor (260 mg of Pd(OAc)$_2$), which showed a significant amount (0.61% in the gas phase) of CO$_2$ in the gas phase. Since water was found to be essential for catalytic activity, it is reason-
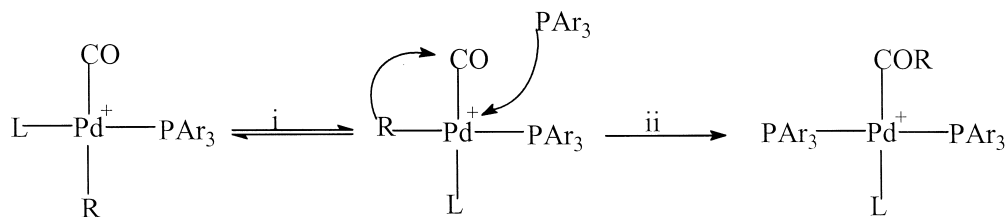

Scheme 3.

able to propose that Eq. (7) is the major pathway for the formation of the active palladium hydride [46–50]. When the amount of water is not sufficient, formation of the hydride will be limited.

Styrene, which is nucleophilic in nature, can co-ordinate to the palladium hydride species through π-co-ordination to form the species **B** (Scheme 2). Coordinated styrene inserts into the Pd–H bond forming either of the two Pd-alkyl intermediates **D** or **E**, whose relative rate of formation depends on the steric as well as the electronic factors as discussed above.

The σ-alkyl complex **D** or **E** on migratory insertion forms the acyl complex, **F** (see Eq. (5)). Earlier studies [51–57] have shown that CO migratory insertion proceeds through intermediates, in which the carbonyl and the alkyl groups are *cis* to each other and the *trans* alkyl complex needs to be converted to the *cis* configuration before migration results (Scheme 3). Increase in the co-ordination ability of the phosphorous ligand (e.g.: PCy_3, PBu_3), *trans* to the alkyl group is known to have retarding effect on the rate of migratory insertion [58]. The labile nature of phosphorous ligand, especially that of PPh_3, helps the migratory insertion by occupying the *trans* position of the migrating alkyl group (step ii) and facilitating the easy migration to CO as shown in Scheme 3. Electron withdrawing ligands like $P(p\text{-}ClC_6H_4)_3$ can retard this effect due to low co-ordination ability. If 'L' or 'PAr$_3$' is strongly bound to the palladium center, the *cis–trans* isomerisation (step i) will not be favored and results in a decreased rate of migratory insertion. Solvents having high co-ordination ability ('L' can be the solvent) have also been reported to retard the migratory insertion and can be one of the reasons for low activity in the case of methyl ethyl ketone and acetone, though the formation of cationic species are enhanced in these solvents.

In principle, also the mechanism as schematised by Eq. (6) may be operative. The beneficial effect of *p*-tsa, even though it does not favor the formation of Pd(COOMe) species as

per the Eq. (3), in increasing the rate of hydrolysis of the Pd–C bond of the intermediate **H** in Eq. (6), yields the product and the carbomethoxy species back to the catalytic cycle. However, this does not explain the beneficial effects of hydrogen and water. For example hydrogen upon activation by the metal cation can split the Pd–C σ-bond of the intermediate **H** giving rise to a Pd–H species:

$$\left[L_n Pd - (C - C - COOMe)\right]^+ + H_2$$
$$\rightarrow \left[L_n Pd\text{–}H\right]^+ + \text{products} \qquad (8)$$
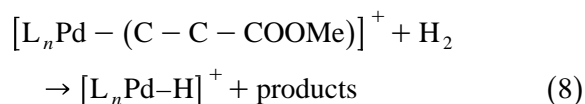
If this is true, then the catalysis should proceed further only through the hydride mechanism. Also, the fact that hydrogen increases the activity without affecting the regioselectivity gives a strong support to the hydride mechanism. The elucidation of reaction mechanism and catalytic cycle based on stoichiometric reactions and isolated intermediate species will be presented in a subsequent paper.

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