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Rhodium catalyzed aqueous biphasic hydroformylation of naturally occurring allylbenzenes in the presence of water-soluble phosphorus ligands

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ABSTRACT

The rhodium-catalyzed hydroformylation of eugenol was performed in aqueous biphasic systems using various water soluble phosphines: TPPTS (triphenylphosphinetrisulphonated); BDPPETS (bisdiphenylphosphinoethanetetrasulphonated), BDPPPTS (bisdiphenylphosphinopropanetetrasulphonated) and BISBIS (diphosphane 2,2′-bis(diphenylphosphinomethyl)-1,1′-biphenyl disuphonated). The addition of the cationic surfactant CTAB (cetyltrimethylammonium bromide) increased the reaction rate; however, high surfactant concentrations unfavorably affected the reaction selectivity. The regioselectivity of the hydroformylation was strongly depended on the ligand nature. The procedure was successfully extended to other allylbenzenes, i.e., estragole and safrole, producing several fragrance compounds starting from the substrates easily available from natural bio-renewable resources.

1. Introduction

Naturally occurring olefins are a green alternative source of renewable feed stocks for chemical industry. One family of naturally occurring olefins is the allylbenzenes such as eugenol (**1a**), estragole (**1b**) and safrole (**1c**) (Scheme 1) obtained from cloves, sweet basil and parsley, respectively. The hydroformylation of allylbenzenes and isomeric propenylbezenes gives aldehydes and alcohols of high added-value with interesting properties that are important in the pharmacological, cosmetic, food and fragrance industries [1–4].

Several groups have studied the hydroformylation of allylbenzenes over the years. Kalck et al. [5] reported the hydroformylation of eugenol, estragole, safrole and eugenol-methyl ether using $[Rh(\mu\text{-}SR)_2(CO)_2L_2]$ as a catalyst precursor (in which L = PPh_3, $P(OPh)_3$ and $P(OMe)_3$) and obtained high regioselectivity towards the linear aldehydes (80–96%).

E. dos Santos and coworkers [1] reported the rhodium catalyzed hydroformylation of various allylbenzenes and propenylbenzenes with 97–99% chemoselectivity in the presence of several phosphorous ligands, such as $P(OPh)_3$, PPh_3, $P(Cy)_3$, $P(CH_2\text{-}Ph)_3$, $P(n\text{-}Bu)_3$, dppe, dppp, dppb, BISBI, and NAPHOS. The activity and regioselectivity of the Rh-monophosphine systems were found to be strongly depended on the basicity of the ligand. In the Rh-diphosphine systems, the regioselectivity correlated with the bite angle of the ligand used, with wide-angled ligands favouring the formation of linear aldehydes.

Paganelli et al. [2] reported the hydroformylation of *m*-diisopropenylbenzene in homogeneous, heterogeneous and biphasic systems as a first step in the preparation of the monoaldehyde Florhydral, a patented, marine-scented fragrance. The hydroformylation in aqueous-toluene biphasic systems was performed with $[Rh(COD)Cl]_2$ or $[Rh(CO)_2(acac)]$ as catalyst precursors and trisulfonated triphenylphosphine (TPPTS) or the biopolymer HSA (human serum albumin) as the ligands.

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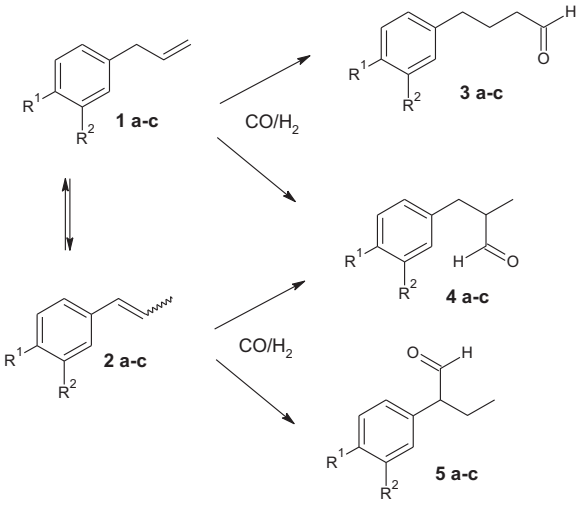

		1	2
a	R^1 = -OH, R^2 = -OCH_3	eugenol	isoeugenol
b	R^1 = -OCH_3, R^2 = H	estragole	anethole
c	R^1 - R^2 = -O-CH_2-O-	safrole	isosafrole

Scheme 1. Hydroformylation of allylbenzenes and propenylbenzenes.

Some of us have shown a great interest in the biphasic hydrogenation and hydroformylation of olefins and light naphtha cuts with water-soluble rhodium, ruthenium, tungsten and molybdenum precursors [6–10]. Recently, we have shifted our focus towards the functionalization of naturally occurring olefins like allylbenzenes and terpenes, readily available from biomass, in biphasic aqueous media and ionic liquids aiming to obtain high added-value products important in the cosmetic, perfume and pharmaceutical industries [11,12]. Aqueous biphasic hydroformylation represents one of the most promising alternatives to overcome the general problem of homogeneous hydroformylation related with the separation of products and high cost rhodium catalysts. This problem is especially crucial for the separation of high-boiling aldehydes derived from allylbenzenes and terpenes because their distillation in the presence of the catalyst could promote the catalyst decomposition and loss of the metal.

The low water solubility of higher alkenes can result in serious restrictions to perform their aqueous biphasic hydroformylation at reasonable rates. In this case, surfactants [13,14] or cyclodextrins [15,16] can be used as one of the most practical and effective strategies to avoid transfer limitations in aqueous/oil biphasic systems. Cationic surfactants provide the most significant effects in Rh/sulfonated phosphine systems as their positively charged moiety directed to the aqueous phase attract the anionic Rh complex to the water/organic phase interface where the catalyst meets the substrate.

In the present work we report the rhodium-catalyzed hydroformylation of eugenol, estragole and safrole in aqueous biphasic systems giving special attention to the effect of the cationic surfactant cetyltrimethylammonium bromide (CTAB) and the nature of water soluble ligands on these reactions.

2. Experimental

2.1. General procedures

Eugenol, estragole, and safrole were purchased from Aldrich and bubbled with argon prior to use. Cetyltrimethylammonium bromide (CTAB) was purchased from Aldrich and used as received. Hydrogen (99.999%) and carbon monoxide (99%) were purchased from Praxair. Bis[(μ-methoxy)(1,5-cyclooctadiene)rhodium(I)] ([Rh(COD)(μ-OMe)]$_2$) [17], TPPTS (triphenylphosphinetrisulphonated) [18]; BDPPETS (bisdiphenylphosphinoethanetetrasulphonated) [19]; BDPPPTS [20] (bisdiphenylphosphinopropanetetrasulphonated) and BISBIS (diphosphane 2,2′-bis(diphenylphosphinomethyl)-1,1′-biphenyl disuphonated) [21], were prepared according to published procedures. Manipulations under argon were made employing Schlenk techniques. Toluene was refluxed with sodium/benzophenone for 8 h. Deionized water was refluxed under argon for 6 h. After treatment, all solvents were distilled and stored under argon.

2.2. Catalytic runs

The catalytic runs were performed in a mechanically stirred stainless steel Parr 4560 bomb coupled with a 4282 control module with a PDI temperature controller, tachometer, and a pressure transducer connected to a field logger apparatus. In a typical experiment the catalyst precursor [Rh(COD)(μ-OMe)]$_2$ (2.5×10^{-6} mol), TPPTS (5.0×10^{-5} mol) and the phase transfer agent cetyltrimethylammonium bromide (CTAB, $0.0–2.0 \times 10^{-4}$ mol) were dissolved in 20 mL of deoxygenated water in a Schlenk tube under argon. The solution was transferred into the bomb, and the substrate ($1.0–2.0 \times 10^{-2}$ mol) was placed in a pressure-equalized reservoir on the top of the bomb. The reactor was pressurized with the desired carbon monoxide pressure (5–20 bar) and then with hydrogen (5–20 bar) up to the desired total pressure. The bomb was heated to the desired temperature (80–120 °C) and kept for one hour under mechanical stirring (750 rpm). The substrate was then added and the register of the syngas pressure drop was initiated. After pressure drop stopped, the reactor was cooled, vented, the organic phase was extracted with toluene (20 mL) and analysed by GC.

2.3. Catalyst recycling

The catalytic runs for recycling were performed in a magnetically stirred stainless steel bomb heated in an aluminum block with a PID temperature control. The catalyst precursor [Rh(COD)(μ-OMe)]$_2$ (2.5×10^{-6} mol), TPPTS (5.0×10^{-4} mol), the phase transfer agent cetyltrimethylammonium bromide, CTAB, (8.0×10^{-4} mol), water (4 mL) and toluene (10 mL) were placed in the reactor. After a pretreatment for two hours under CO/H_2 (1:1, 20 bar) at 80 °C, the pressure was released and eugenol (2×10^{-3} mol) was introduced though a ball valve under argon flow. The reactor was pressurized again with CO/H_2 (1:1, 20 bar), let react for 2 h at 100 °C, cooled at room temperature, and then depressurized. The contend was transferred into a Schlenk tube under argon flow. The lower (water) phase was collected with a syringe and reintroduced in the reactor. A fresh portion of eugenol (2×10^{-3} mol) in toluene (10 mL) was introduced and the reactor was pressurized again for a new cycle. The organic phase was analysed by GC.

2.4. Product analysis

The products were quantitatively analyzed by gas chromatography (GC) using a Shimadzu GC2010 instrument equipped with a split/splitless injection port and flame ionization detector, fitted with a RestekRtx-wax capillary column (30 m × 0.25 mm × 0.25 μm). Conversion and product distribution were determined by GC. The mass balance was checked employing dodecane as internal standard.

Qualitative analysis of the known products was made by GC coupled with mass spectrometry in a Shimadzu GC2010/QP2010-plus instrument fitted with a Restek Rtx-5 MS capillary column (30 m × 0.25 mm × 0.25 μm), operating at 70 eV.

3. Results and discussion

The hydroformylation of eugenol (**1a**) as a model for naturally occurring allylbenzene family has been studied in aqueous biphasic systems in the absence of additional organic solvents using $[Rh(COD)(\mu\text{-}OMe)]_2$ as the catalyst precursor and various water soluble ligands (TPPTS, BDPPETS, BDPPPTS and BISBIS) to keep the catalyst dissolved in the aqueous phase. For comparison, the reaction was also performed in a conventional homogeneous system with triphenylphosphine (TPP) as the auxiliary ligand. The reactions with estragole (**1b**) and safrole (**1c**) were performed in biphasic systems under optimized conditions.

All three substrates gave two major products derived from the direct carbonylation of their terminal double bonds: linear and branched aldehydes (**3a–c** and **4a–c**, respectively, Scheme 1). Corresponding propenylbenzenes **2a–c**, formed due to the substrate isomerization, were detected as minor products along with trace amounts of the products of substrate hydrogenation (not shown in Scheme 1). The hydroformylation of propenylbenzenes **2a–c** would give branched aldehydes **4a–c** and **5a–c** with the formyl group in β-and α- positions, respectively; however, α-isomers **5a-c** were formed only in small amounts because of the lower reactivity of internal olefins in hydroformylation.

The comparison of relative hydroformylation rates in various runs was made by measuring the pressure drop of syngas inside the reactor along the reaction time. The internal pressure was measured through a pressure transducer and automatically logged by a field logger connected to a computer. Kinetic curves were nearly straight lines up to ca. 90% conversions in most of the runs, what indicates that the reaction rate is independent on the substrate concentration. The reported rates correspond to the slope of the curves in their linear part (stationary period of the reaction).

3.1. Hydroformylation of eugenol in the absence of the surfactant

In the presence of small amounts of TPPTS (P/Rh = 3), the hydroformylation of eugenol occurred smoothly under mild conditions (100 °C, 20 bar) resulting in a full substrate conversion within 2 h to give aldehydes **3a**, **4a** and **5a** with a 78% combined selectivity (Table 1, run 1). The isomeric propenylbenzene, isoeugenol **2a**, was responsible for almost all the rest of the mass balance. The effect of the ligand concentration is illustrated by runs 1–4 in Table 1. It is remarkable that the increase in the P/Rh atomic ratio from 3 to 20 has resulted in a strong enhancement of the reaction rate as well as improved the chemoselectivity for the aldehydes to 97%. Although the results suggested that the TPPTS/Rh ratio higher than 20 could be beneficial for the system, we have decided to carry the studies with P/Rh = 10 to spare the ligand during the screening of the conditions. The regioselectivity was nearly 70% for linear aldehyde **3a** within the whole range of ligand concentrations used, with α-aldehyde **5a** being formed in very small amounts.

It is important to note that the performance of the Rh/TPPTS biphasic system was comparable to that of the conventional homogeneous Rh/TPP system under similar conditions (Table 1, cf. run 3 and 5; P/Rh = 10). Both homogeneous and biphasic reactions showed high averaged turnover frequencies (TOF) of 6660 and 5000 h^{-1}, respectively. At P/Rh = 20 (Table 1, run 4), the reaction in the biphasic system was even faster (TOF = 8000 h^{-1}).

The total pressure of the equimolar gas mixture had a strong positive effect on the rate of the hydroformylation of eugenol (Table 1, runs 3, 6 and 9). Typically, the increase in the total pressure does not affect significantly the hydroformylation rate because either the rate-determining step is prior to the hydrogen addition or CO has a negative order, competing with hydrogen for the metal sites and thus resulting in a compensative effect if both gases have the same increase in their partial pressures.

In addition to the total pressure effect, we examined the effects of different partial pressures (different CO/H_2 ratios) on the hydroformylation rate (Table 1, runs 3, 7 and 8). It is interesting to observe that the rate is roughly first order with respect to the hydrogen pressure, but quite insensitive (nearly zero order) to the CO pressure. For example, in run 8, the hydrogen pressure was 1.8 times higher than that in run 7, and the rate was also 1.8 times higher in spite of the difference in the CO pressure. In run 9, the hydrogen pressure was doubled as compared to run 3, which resulted in two times increase in the reaction rate. On the other hand, the rate of the reaction at 10 atm of the equimolar gas mixture was disproportionably lower (four times lower) than that at 20 atm (Table 1, runs 6 and 3). Thus, the existence of mass transference limitations could not be ruled out in the biphasic systems at low gas pressure.

The selectivity for the aldehydes was higher than 93% in all the runs presented in Table 1, except for run 1 and run 6, which were performed at either low ligand concentration (P/Rh = 3 in run 1) or low gas pressure (10 atm in run 10). On the other hand, the highest regioselectivity of 81% for linear aldehyde **3a** was obtained in run 6.

The results obtained can be interpreted in the light of the putative mechanism for the rhodium-catalyzed hydroformylation of terminal olefins. After initiation, i.e., the formation of the square-planar [RhH(CO)(L)(L')] species (L, L' = CO or P(III) ligand), the expected organometallic steps are: (i) substrate coordination; (ii) hydride migration to form linear or branched metal-alkyl species; (iii) CO coordination; (iv) migration of the alkyl moiety to the coordinated CO to form metal acyl species; (v) oxidative addition of hydrogen to metal acyl species; vi) reductive elimination of the aldehyde. The latter step (vi) is considered to be essentially irreversible, while the others may be reversible, depending on substrates and reaction conditions. From the branched metal-alkyl species formed during step (ii), a β-hydrogen elimination, instead of step (iii), may lead to isomeric olefins. Thus, if in any step of the hydroformylation the path after the hydride migration (i) is hindered, the tendency is to increase the importance of the isomerization path.

In rhodium systems promoted by monodentate phosphorus(III) ligands, the active species shown in Eqn. 1 are formed. Considering the geometric isomers of the square–planar $[RhH(CO)(L)_2]$ complex, four active species can be formed, with their concentrations being depending on both the CO pressure and ligand L concentration. The activity and selectivity of the system will be the combination of the activities and selectivity of the individual species taking into account their concentrations.

$$[RhH(CO)_3] \underset{+\,CO,\,-\,L}{\overset{-\,CO,\,+\,L}{\rightleftharpoons}} [RhH(CO)_2(L)] \underset{+\,CO,\,-\,L}{\overset{-\,CO,\,+\,L}{\rightleftharpoons}} [RhH(CO)(L)_2] \quad (1)$$

At low ligand concentrations, the equilibrium in Eq. (1) tends to the left, and in average the rhodium species tend to have less electron density. Thus, the hydrogen oxidative addition will be more difficult and, as a consequence, the hydroformylation rate will

Table 1
Hydroformylation of eugenol (**1a**) under biphasic conditions[a]

Run	P/Rh[b]	Pressure/bar	pH_2/bar	pCO/bar	Rate[c] /bar min^{-1}	Time/ min[d]	Aldehyde selectivity[e]	Regioselectivity		
								3a	**4a**	**5a**
1	3	20	10	10	0.06	120	78	73	26	1
2	5	20	10	10	0.09	40	93	71	28	1
3	10	20	10	10	0.15	24	95	73	26	1
4	20	20	10	10	0.24	15	97	73	26	1
5	10[f]	20	10	10	0.20	18	95	71	29	0
6	10	10	5	5	0.04	105	80	81	18	1
7	10	20	7	13	0.13	40	95	72	28	1
8	10	20	13	7	0.24	15	95	76	23	0
9	10	40	20	20	0.29	12	98	72	27	1

[a] Conditions: eugenol (1.0×10^{-2} mol); $[Rh(cod)(\mu\text{-}OMe)]_2$ (2.5×10^{-6} mol), TPPTS ($1.5–10.0 \times 10^{-5}$ mol); water (20 mL); 100 °C.
[b] Phosphorus/rhodium atomic ratio.
[c] Rate of syngas pressure drop taken on the stationary period.
[d] Time to reach pressure stabilization (complete conversion).
[e] Other products are *cis* and *trans* double-bond isomers (**2a**) and a small amount of dihydroeugenol.
[f] Triphenylphosphine(5.0×10^{-5} mol) as ancillary ligand in toluene (20 mL) as the only solvent.

decrease and the isomerization path will be more favored. These tendencies were observed in run 1, Table 1. With the increase in the ligand concentration (Table 1, runs 2–4), the equilibrium tends to the right, increasing the contribution of the species in which the oxidative addition of hydrogen is more favored. Thus, the hydroformylation rate will be favored detrimentally to the isomerization rate.

For the hydroformylation of terminal double bonds in the Rh/TPP systems, a maximum activity is usually reached at P/Rh < 10. However, in the present study, the promoting effect of TPPTS increased at least up to P/Rh = 20. A plausible explanation could be that TPPTS has a larger cone angle (170°) than TPP (145°) [22]. Phosphorous ligands compete with CO, which is a strong ligand, so the increase in the concentration of the more active bisligand $[RhH(CO)(L)_2]$ species is only guaranteed at high P/Rh atomic ratios in the case of bulky TPPTS. On the other hand, the formation of the trisligand $[RhH(CO)(L)_3]$ species at high ligand concentrations, which would be detrimental to the catalyst activity, is disfavored by the large cone angle of TPPTS.

The positive order in hydrogen and nearly zero order in CO can be explained assuming that CO does not compete significantly with hydrogen for the metal sites in the rhodium-acyl species formed in step (iv), and the metal acyl intermediates preferably undergo hydrogenolysis (steps v + vi) rather than be trapped by CO to form the inactive $[Rh(acyl)(L)(L')(CO)_2]$ species.

The increase in regioselectivity and decrease in aldehyde chemoselectivity observed in run 6 may be due to the low CO pressure: on one hand, the branched metal-alkyl intermediate is more difficult to render alkyl migration to the coordinated CO (step iv) and, on the other hand, at low CO pressure there could be a vacant site *cis* to the alkyl group and β-elimination rather than carbonylation could take path. The analogous explanation could be valid for the slight increase in regioselectivity in run 8 (low CO pressure) and the higher aldehyde selectivity in run 9 (high CO pressure).

3.2. Hydroformylation of eugenol in the presence of the surfactant CTAB

Although the hydroformylation of eugenol could be performed in biphasic systems even in the absence of the surfactant due to its relatively high hydrophilicity, the use of the cationic surfactant was beneficial (Table 2). The addition of small amounts of CTAB (1.0 mM, considering only the volume of the aqueous phase) accelerated the reaction significantly, promoting a complete conversion of eugenol in 20 min with excellent selectivity of 95% for the aldehydes (Table 2, run 10 vs. run 3). At CTAB concentration of 2.0 mM, the reaction rate was more than doubled as compared to the run without the surfactant (Table 2, run 11 vs. run 3); however, further addition CTAC up to 10.0 mM had a slight negative effect on the reaction rate (Table 2, runs 12 and 13 vs. run 11). In run 13 at 10.0 mM of the surfactant, a 5 min induction period was observed on the kinetic curve.

The presence of the surfactant results in the increase in the interfacial area due to the formation of a micellar system and, as a consequence, increases the reaction rate. The increment of the concentration of CTAB increases the number of micelles and the interfacial area favouring the hydroformylation reaction. This behaviour is in agreement with that reported previously by some of us employing cetyltrimethylammonium chloride (CTAC) [23]. In addition, the positively charged moieties of CTAB directed to the aqueous phase attract the Rh complex through electrostatic interactions with the anionic sulfonate group of the TPPTS ligand, thus increasing the rhodium concentration in the interface and accelerating the reaction. However, at higher surfactant concentrations, the micelles begin to expand and microemulsions might be formed which would be detrimental for the interfacial area. The critical micelle concentration (CMC) is defined as the minimum concentration of surfactant from which the micelles are formed and it is characteristic of each system. In our studies we determined a CMC of 0.6×10^{-3} M, the value which is in accordance with the data reported by Li and co-workers [24–26]. The increase in the surfactant concentration produces a change in their structure to form cylindrical-shaped micelles with less superficial area than the spherical-shaped micelles [27], disfavoring by this reason the reaction rate.

The slight decrease in activity observed in runs 12 and 13, as well as the induction period in run 13, could also be related with the negative effect of the bromide ions (the counter-ion of CTAB) that may be competing with the substrate for the coordination sites on rhodium at higher CTAB concentrations. The increase in the surfactant concentration also resulted in the significant decrease in the selectivity for aldehydes. These results support the suggestion that the bromide ions interact with rhodium species changing their catalytic properties. The hydroformylation of eugenol was performed at different temperature (Table 2, runs 10, 14 and 15). As a result, we decided to use the CTAB concentration of 1.0 mM and temperature of 100 °C in our further studies to take advantage of the improved reaction kinetics without the loss in the hydroformylation selectivity.

The beneficial effect of the surfactant on the hydroformylation of eugenol in the biphasic system was also clearly pronounced in the reactions with the doubled amounts of the substrate (Table 2, runs 16 and 17). The kinetic curves for the reactions performed with and without the surfactant at both substrate concentrations

Table 2
Hydroformylation of eugenol (**1a**) under biphasic conditions in the presence of CTAB[a]

Run	CTAB/mol × 10^5	CTAB/mM	CTAB / TPPTS[b]	Temp/°C	Rate [c]/bar min^{-1}	Time/ min[d]	Aldehyde selectivity[e]	Regioselectivity		
								3a	**4a**	**5a**
3	0.0	0.0	0.0	100	0.15	24	95	73	26	1
10	2.0	1.0	0.4	100	0.22	20	95	70	27	3
11	4.0	2.0	0.8	100	0.33	20	85	76	20	4
12	8.0	4.0	1.6	100	0.31	20	80	74	22	4
13	20.0	10.0	4	100	0.29	20[f]	73	64	34	2
14	2.0	1.0	0.4	80	0.11	60	97	73	26	1
15	2.0	1.0	0.4	120	0.26	15	83	72	25	3
16[g]	0.0	0.0	0.0	100	0.15	80	90	71	28	1
17[g]	2.0	1.0	0.4	100	0.22	40	90	71	28	1

[a] Conditions: eugenol(1.0×10^{-2} mol); $[Rh(cod)(\mu\text{-}OMe)]_2$ (2.5×10^{-6} mol), TPPTS (5.0×10^{-5} mol); CTAB ($0.0–20.0 \times 10^{-5}$ mol); water (20 mL); CO/H_2 (1:1, 20 bar); 100 °C.
[b] Molar ratio.
[c] Rate of syngas pressure drop taken on the stationary period.
[d] Time to reach pressure stabilization (full conversion).
[e] Other products are *cis* and *trans* double-bond isomers (**2a**) and a small amount of dihydroeugenol.
[f] Induction period of 5 min was observed.
[g] Eugenol (2.0×10^{-2} mol).

are presented in Fig. 1 (Table 2, runs 3, 10, 16 and 17). As it can be seen from the slopes, the reaction is zero order with respect to the substrate concentration. It is important to note that high turnover numbers (substrate to rhodium ratio of up to 4000) as well as the linearity of the kinetic curves until nearly complete conversions illustrate the excellent stability of the catalytic system under the biphasic conditions.

3.3. Hydroformylation of eugenol in the presence of water soluble diphosphines

One of the main aims in this research was to increase the selectivity to the branched aldehydes because of their special importance for the fragrance industry. Some of us previously reported that the use of diphosphines with bite angles nearly 90° such as DPPE (85°) and DPPP (91°), can significantly increase the selectivity to branched aldehydes at the hydroformylation of eugenol in homogeneous systems [1]. Encouraged by these results, we decided to use sulfonated analogues of these diphosphines, i.e., BDPPETS, BDPPPTS and BISBIS, in aqueous biphasic systems in order to control the regioselectivity of the hydroformylation (Table 3, runs 18, 19 and 20). For comparison, the run with TPPTS under similar conditions is also presented in Table 3 (run 10).

Although the reactions employing BDPPETS and BDPPPTS as ancillaries were much slower than that with TPPTS, the regioselectivity of nearly 60% for branched aldehyde **4a** was achieved at complete substrate conversions (Table 3, runs 18 and 19). To the best of our knowledge, these results are among the best reported so far for the hydroformylation of allylbenzenes in terms of regioselectivity for branched aldehydes with the formyl group in β-position [1,28]. On the other hand, the reaction with BISBIS gave linear aldehyde **3a** almost exclusively and occurred at the rate comparable with that of the reaction with TPPTS (Table 3, run 20).

It is well established that for the wide-angled BISBIS ligand (123°), a diequatorial chelation is expected and the corresponding trigonal–bipyramidal intermediate tends to form the linear aldehyde [22]. Less explored is why bite angles of nearly 90° such as of the BDPPETS and BDPPPTS ligands favour the formation of branched aldehydes. Whether it is a purely steric, electronic, a π-staking effect or a combination of these effects is an open question and it is a current research interest for Belo Horizonte's group.

3.4. Hydroformylation of other allylbenzenes

The hydroformylation of estragole (**1b**) and safrole (**1c**) was performed in the biphasic system under optimized conditions (Table 3, runs 21 and 22). Both substrates gave linear (**3b** and **3c**) and

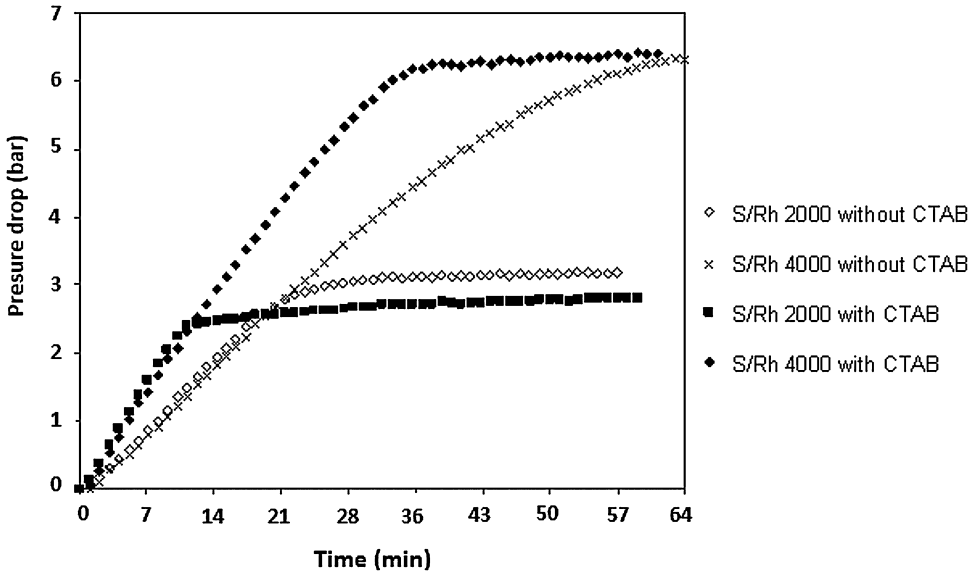

Fig. 1. Syngas uptake in 1a hydroformylation with and without CTAB. (For conditions see Table 2, entries 3, 10, 16, 17).

Table 3
Hydroformylation of allylbenzenes (**1a–c**) under biphasic conditions promoted by water-soluble phosphines[a]

Run	Substrate	Ligand	Ligand/Rh [b]	Substrate solubility[c] /g L^{-1}	Rate [d] /bar min^{-1}	Time/ min[e]	Aldehyde selectivity[f]	Regioselectivity		
								3a–c	**4a–c**	**5a–c**
18	**1a**	DPPETS	5	1.8	0.05	105[g]	99	42	58	0
19	**1a**	DPPPTS	5	1.8	0.03	150[g]	94	37	60	3
20	**1a**	BISBIS	5	1.8	0.16	30	92	92	7	1
10	**1a**	TPPTS	10	1.8	0.22	20	95	70	27	3
21	**1b**	TPPTS	10	0.64	0.06	120	89	71	29	0
22	**1c**	TPPTS	10	0.16	0.02	480	85	72	27	1

[a] Conditions: substrate (1.0×10^{-2} mol); [Rh(cod)(μ-OMe)]$_2$ (2.5×10^{-6} mol), ligand ($2.5–5.0 \times 10^{-5}$ mol); CTAB (2.0×10^{-5} mol); water (20 mL); CO/H$_2$ (1:1, 20 bar); 100 °C.
[b] Molar ratio; P/Rh atomic ratio is 10 for all experiments.
[c] Solubility of the substrate in water, 25 °C, pH = 1–9.
[d] Rate of syngas pressure drop taken on the stationary period.
[e] Time to reach pressure stabilization (full conversion).
[f] Other products are *cis* and *trans* double-bond isomers (**2a–c**) and a small amount of hydrogenated substrate.
[g] Induction period of 10 min was observed.

Table 4
Hydroformylation of eugenol (**1a**) under biphasic conditions: recycling experiments[a]

Run	Catalyst use	Conversion[b] /%	Aldehyde selectivity[b,c] /%	Regioselectivity[b] /%		
				3a	**4a**	**5a**
23	1st	64	96	85	15	0
24	2nd	62	95	85	15	0
25	3rd	66	98	83	17	0
27	4th	53	97	84	16	0
28	5th	47	97	83	17	0
29	6th	46	95	83	17	0

[a] Conditions: eugenol (2.0×10^{-3} mol); [Rh(cod)(μ-OMe)]$_2$ (2.5×10^{-6} mol), TPPTS (5.0×10^{-4} mol); CTAB (8.0×10^{-5} mol) water (4 mL); toluene (10 mL); CO/H$_2$ (1:1, 20 bar); 100 °C; 2 h.
[b] Determined by GC.
[c] Other products are *cis* and *trans* double-bond isomers (**2a**).

branched (**4b** and **4c**) aldehydes as major products with nearly 70% regioselectivity for the linear isomers at complete conversions. The combined selectivity for the hydroformylation products was 85–89%, with corresponding propenylbenzenes **2b** and **2c** being responsible for the rest of the mass balance. The reactions with estragole and safrole occurred much slower than that with eugenol. An attempt to explain this difference by the electronic properties of the substituents in the aromatic ring could be valid. However, we believe that the decisive parameter affecting the reactivity of the allylbenzenes in the aqueous biphasic system is their solubility in water, which, in its turn, is influenced by the nature of the functional groups attached to the aromatic rings. Really, a clear correlation between the reaction rate and water solubility can be seen for all three substrates (Table 3, runs 10, 21 and 22). The reactivity of the less soluble substrate safrole was ca. 10 times lower than the reactivity of eugenol, the most soluble substrate. However, safrole was successfully hydroformylated in the biphasic aqueous system under the optimized conditions in the presence of the surfactant.

3.5. Catalyst recycling

In order to proof the recyclability principle of the catalyst system, we used a different type of reactor, which allows a manipulation equivalent to that of a Schlenk tube in order to avoid oxygen contamination during the recycles. We also chose a set of experimental conditions based on this work, i.e., a high phosphorus/rhodium atomic ratio and medium CTAB concentration, combined with the ones developed by some of us in a recent publication [29]: a lower volume for the aqueous phase combined with a non polar co-solvent (toluene). The reaction time of two hour was chosen to deliberately avoid full conversion and allow the comparison of the catalytic activity among the cycles from the conversion values. The recycling experiments are presented in Table 4.

At such a high phosphorus/rhodium atomic ratio, the activity was reduced, but the chemoselectivity for aldehydes and the regioselectivity for the linear aldehydes increased as compared to the ones of Table 2 (*c.f.* runs 12 and 13). The conversions were essentially maintained in the first three uses of the catalyst, but dropped in the fourth use. It is noteworthy that the conversion values seemed to stabilize after that. The organic phase of the fifth use was recycled and let react with a fresh portion of substrate and no evolution on products was observed after two hours at 100 °C and 20 bar of CO/H$_2$ (1:1). Although the rhodium leaching cannot be completely ruled out, these experiments show that this catalytic system can be recycled at least five times keeping good activity and selectivity.

4. Conclusions

Eugenol, a bio-renewable substrate available from natural essential oils, can be hydroformylated in a conventional surfactant-free aqueous biphasic system at a reasonable rate with excellent selectivity in the absence of any organic solvent. The addition of small amounts of the cationic surfactant CTAB significantly accelerated the reaction; however, at high concentrations the surfactant unfavorably affected the selectivity of hydroformylation. The ratio between the linear and branched aldehydes (l/b ratio) can be controlled by the nature of water soluble phosphorous ligands. The conventional TPPTS ligand provided the preferential formation of the linear aldehyde ($l/b \approx 2.5$), while with the sulfonated diphosphines BDPPETS and BDPPPTS regioselectivity was switched to the branched isomer ($l/b \approx 0.6$). On the other hand, the wide-angled sulfonated diphosphine BISBIS favored the almost exclusive formation of the linear aldehyde ($l/b \approx 12$). This simple and green one-pot procedure was successfully extended to other allylbenzenes, i.e., estragole and safrole, producing several fragrance compounds starting from naturally occurring substrates. The rhodium catalyst immobilized in water, an environmentally benign solvent, can

be easily separated after the reaction from the organic phase and recycled for at least five times without significant loss in activity or selectivity.

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