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Hydroformylation of unsaturated esters and 2,3-dihydrofuran under solventless conditions at room temperature catalysed by rhodium *N*-pyrrolyl phosphine catalysts†

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Rhodium complexes of the type $HRh(CO)L_3$ (where L is an *N*-pyrrolyl phosphine, such as $P(NC_4H_4)_3$, $PPh(NC_4H_4)_2$, or $PPh_2(NC_4H_4)$) were applied in the hydroformylation of less reactive unsaturated substrates, namely allyl acetate, butyl acrylate, methyl acrylate, 2,3-dihydrofuran and vinyl acetate. Even at room temperature, these catalysts enabled complete substrate conversion and high chemoselectivity towards the corresponding aldehydes. High conversion of vinyl acetate (88% in 6 h) to the branched aldehyde was obtained with $HRh(CO)[P(NC_4H_4)_3]_3$ at 25 °C. An increase of the turnover frequency, TOF, up to 2000 mol mol^{-1} h^{-1} was achieved in this reaction under 20 bar of syngas (H_2/CO = 1) at 80 °C. The introduction of chiral phosphines, BINAP or Ph-BPE, to this system resulted in the production of a branched aldehyde with enantioselectivity, ee, up to 44 and 81%, respectively. High activity combined with high enantioselectivity was achieved due to the formation of the mixed rhodium hydrides $HRh(CO)[P(NC_4H_4)_3]$(BINAP) and $HRh(CO)[P(NC_4H_4)_3]$(Ph-BPE), identified by the NMR method.

Introduction

The hydroformylation of alkenes is one of the widest-ranging processes in the industrial application of homogeneous catalysis, which allows for the conversion of alkenes into aldehydes in a single catalytic step by using hydrogen and carbon monoxide.[1–5] The hydroformylation of functionalized alkenes is an attractive synthetic method for the production of bifunctional compounds.[6] Unfortunately, the serious limitation of this method is the low reaction rate and low chemoselectivity to aldehydes. Due to the electronic structure, hydroformylation of unsaturated esters produced the branched aldehyde as the main product.[7] Wilkinson *et al.* reported that the hydroformylation of vinyl acetate catalyzed by $HRh(CO)(PPh_3)_3$ is significantly less efficient than that of terminal alkenes.[8] Not only vinyl acetate but also other unsaturated esters are significantly less reactive to CO/H_2 than 1-alkenes.[1–5] Therefore, harsher conditions and a longer time should be used to transform them to aldehydes. On the other hand, the hydroformylation of esters presents an attractive method leading to valuable products containing two functional groups. Aldehydes formed in the hydroformylation of vinyl acetate can be further converted into synthetically useful compounds, such as 1,2- and 1,3-propanediol, lactic acid, ethyl lactate,[9,10] amino acid threonine,[11,12] and 2-hydroxypropanal, a very useful building block for the synthesis of steroids, antibiotics, and peptides.[12] Aldehydes obtained from allyl acetate hydroformylation can be easily converted into 1,3- and 1,4-diols, which have a wide range of applications.[6] Moreover, isoaldehydes produced by the hydroformylation of methyl or butyl acrylate are very important building blocks for the synthesis of biologically active compounds, such as malonic acid, 1,4-dicarboxylic acids, and lactones.[13–15] Optically active 2- and 3-carbaldehydes can be synthesized in one step in the asymmetric hydroformylation of 2,3-dihydrofuran.[16] These chiral aldehydes can be utilized as substrates in the preparation of biologically active natural products and pharmaceuticals, such as amprenavir, terazosin, and CCR5 antagonist.[17]

Rhodium(I) complexes modified with *N*-pyrrolylphosphine ligands have been successfully applied for the hydroformylation of different alkenes, such as 1-hexene,[18–22] vinylsilanes,[23] 2-pentene,[24] ethane,[25] dicyclopentadiene,[26] α-methylstyrene,[27] 1-butene,[28] and propene.[29] In all cases, high selectivity towards aldehydes was achieved. These reactions have been carried out in organic solvents[18–29] and, in a few cases, also in a mixture of toluene and water.[28,29]

Our previous study evidenced that a solventless procedure was very efficient in the hydroformylation of olefins and unsaturated alcohols, providing high conversion and chemoselectivity towards aldehydes.[22,30–33] The main advantage of the

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solventless procedure is the simplification of the process by the elimination of the organic solvent, following the green chemistry rules.

In this paper, we for the first time report on the hydroformylation of unsaturated esters, such as vinyl acetate, allyl acetate, butyl acrylate, and methyl acrylate, as well as 2,3-dihydrofuran, catalyzed by $HRh(CO)L_3$ [where L = $P(NC_4H_4)_3$, $PPh(NC_4H_4)_2$, or $PPh_2(NC_4H_4)$] under solventless conditions and without excess phosphine. We found that these catalysts were able to efficiently form aldehydes from less active substrates even at room temperature.

Experimental

Chemicals

Rhodium complexes $Rh(acac)(CO)_2$[34] and $HRh(CO)[P(NC_4H_4)_3]_3$ **I**[28] were synthesized according to the literature procedure. Hydrido-rhodium complexes $HRh(CO)[PhP(NC_4H_4)_2]_3$ **II** and $HRh(CO)[Ph_2P(NC_4H_4)]_3$ **III** were prepared by using the same procedure.[28] The *N*-pyrrolylphosphine ligands $P(NC_4H_4)_3$, $PPh(NC_4H_4)_2$, and $PPh_2(NC_4H_4)$ were synthesized as described in the literature.[35] Vinyl acetate was purchased from Fluka; allyl acetate, 2.3-dihydrofuran, butyl acrylate, BINAP and Ph-BPE were purchased from Aldrich; methyl acrylate was purchased from International Enzymes Limited; and hydrogen (H_2, 99.999%) and carbon monoxide (CO, 99.97%) were procured from Air Products. All chemicals were used without any additional purification.

Hydroformylation reactions

The hydroformylation reactions were performed in 50 ml stainless steel autoclaves provided with manometers, thermostats, and magnetic stirrers. The required amounts of catalysts **I**, **II**, or **III** were placed in the autoclave under a nitrogen atmosphere. The substrate (1 mL) was introduced. The autoclave was sealed; hydrogen (5 bar) was passed through three times; and thereafter the autoclave was pressurized with syngas (H_2/CO = 1) to 20 bar and heated to the desired temperature. After the reaction was completed, the autoclave was cooled to room temperature and the residual gases were depressurized. The organic products were separated by the vacuum transfer procedure and analyzed by means of GC, GC-MS, and NMR.

Results and discussion

Synthesis of rhodium complexes

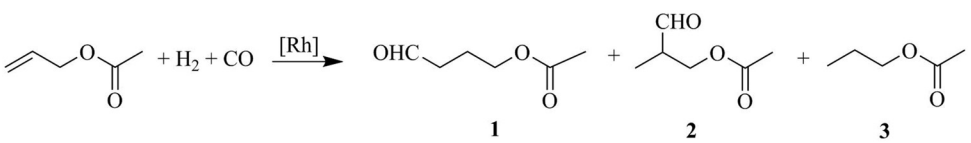
The hydrido-carbonyl complexes $HRh(CO)[P(NC_4H_4)_3]_3$ **I**, $HRh(CO)[PhP(NC_4H_4)_2]_3$ **II**, and $HRh(CO)[Ph_2P(NC_4H_4)]_3$ **III** were synthesized by the reaction of $Rh(acac)(CO)_2$ with *N*-pyrrolylphosphines under syngas (H_2/CO) following the procedure reported earlier for $P(NC_4H_4)_3$.[28] The structures of the complexes were confirmed by IR spectra showing two bands for ν(CO) and ν(Rh–H) vibrations, at 2073.9 cm^{-1} and 1987.7 cm^{-1} for **I**, at 2052.7 cm^{-1} and 1970.8 cm^{-1} for **II**, and at 2039.7 cm^{-1} and 1948.1 cm^{-1} for **III**, respectively (Fig. S1–S3, ESI†).

Hydroformylation of allyl acetate

The hydroformylation of allyl acetate catalysed by the three hydrido complexes **I**, **II**, and **III** under solventless conditions in the absence of any additional excess free ligands was investigated under 20 bar of H_2/CO = 1. Two aldehydes, 4-acetoxybutanal, linear aldehyde **1**, and 3-acetoxy-2-methyl propanal, isoaldehyde **2**, were obtained as the main products with a small amount (about 1–2%) of propyl acetate (hydrogenation product, **3**) (Scheme 1).

The results obtained at 25 and 80 °C are reported in Table 1. At room temperature the catalytic activity of **I**, **II**, and **III** differed, as shown in Fig. 1. Complete substrate conversion was obtained with catalyst **I** in 2 h, while 94% converted to the corresponding aldehyde in 8 h when using catalyst **II**. Only 15% of the allyl acetate reacted in the case of catalyst **III** in 14 h. In all cases, the yield of the branched aldehyde **2** was higher than that of the linear one, **1**. For comparison, we carried out hydroformylation of allyl acetate with catalyst **I** at room temperature using toluene as a solvent. In this reaction the conversion was 59% and the regioselectivity to the linear aldehyde (1/2 ratio) was equal to 0.63 (Table 1, entry 3). Significantly better results were achieved under solventless conditions, with 100% conversion and the regioselectivity to the linear aldehyde (1/2 ratio) equal to 0.8 (Table 1, entry 2). The high efficiency of catalysts **I** and **II** at room temperature for hydroformylation of allyl acetate is unusual. Good results for this reaction were obtained at 40 °C, but at a higher pressure, 4 MPa ($CO:H_2 = 1:1$).[6] High conversion and selectivity to linear aldehydes were obtained at 120 °C in toluene.[48] Allyl acetate was converted to the corresponding aldehydes with yields of 3% and 99% respectively at 60 °C and 80 °C using 30 bar of syngas ($CO/H_2 = 1/5$) for 4 h in toluene.[49]

The complete conversion of allyl acetate was obtained at 80 °C in 20 min by using catalysts **I** or **II** with the same excellent selectivity towards aldehydes and high TOF values. Interestingly, the higher temperature promoted better regioselectivity towards the linear aldehyde and with catalyst **I** the **1**/**2** ratio was 1.8, while with catalyst **II** it was 1.04 (Table 1, entries 1 and 3). It should be mentioned that catalysts **I** and **II** preferably formed an *n*-aldehyde, while an isoaldehyde was mainly formed with other catalysts.[6] With catalyst **III**, a longer time, 50 min, was



Scheme 1 Hydroformylation of allyl acetate.

Table 1 Hydroformylation of allyl acetate catalysed by catalysts **I**, **II**, and **III** under solventless conditions[a]

Entry	Catalyst	T, °C	t	Conv., %	Product distribution 1%[c]	2%[d]	**1**/**2** ratio	TOF,[e] mol mol^{-1} h^{-1}
1	**I**	80	20 min	100	63	35	1.8	2376
2		25	2 h	100	43	56	0.8	396
3[b]		25	2 h	59	39	61	0.6	236
3	**II**	80	20 min	100	50	48	1.04	2376
4		25	8 h	94	33	66	0.5	93
5	**III**	80	50 min	100	40	59	0.7	954
6		25	14 h	15	26.7	73.3	0.4	8.6

[a] Reaction conditions: allyl acetate (1 mL), [substrate]/[Rh] = 800, P = 20 bar (H_2/CO = 1). [b] Toluene as the solvent. [c] Selectivity to 4-acetoxybutanal. [d] Selectivity to 3-acetoxy-2-methyl propanal. [e] TOF = (mole of products (**1** + **2**))/(mole of catalyst × reaction time).

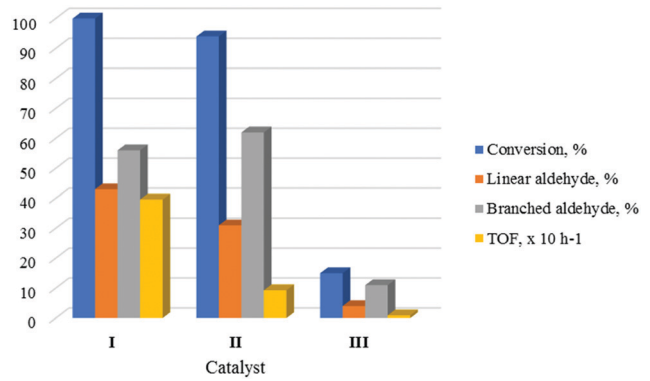


Fig. 1 Hydroformylation of allyl acetate at room temperature.

needed to achieve 100% conversion; however, lower selectivity and TOF values were noted (Table 1, entry 5).

A further increase in the regioselectivity towards the linear aldehyde was achieved upon the addition of excess $P(NC_4H_4)_3$ to **I** (Table S1, ESI†).

Hydroformylation of butyl and methyl acrylate

The typical pattern of acrylate ester hydroformylation is shown in Scheme 2. Butyl and methyl acrylates mainly produced branched aldehyde **1**. Smaller amounts of linear aldehyde **2** and propionic ester were also formed.

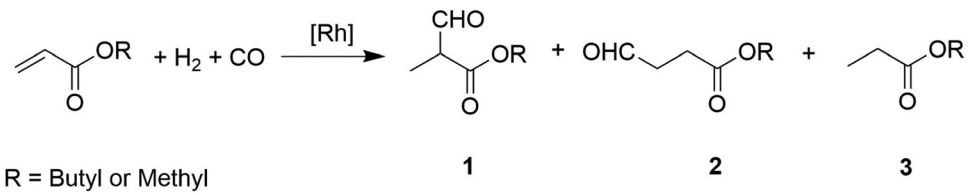
Excellent chemoselectivity and regioselectivity towards the isoaldehyde were obtained in the hydroformylation of butyl acrylate at room temperature (Table 2, entries 1, 3 and 4). The isoaldehyde was obtained under these conditions as the only product with catalyst **I**. Lower chemoselectivity was achieved with catalysts **II** and **III**, however, the yield of the isoaldehyde was still higher than that of the linear one with a **1**/**2** ratio of 37.5 and 9.4. Methyl acrylate reacted differently and the hydroformylation chemoselectivity was lower mainly because of the significant contribution of the hydrogenation process leading to methyl propionate **3**. The yield of **3** increased to 49.8% and 87.5% for catalysts **II** and **III** (Table 2, entries 7 and 8). Interestingly, at room temperature only catalyst **I** effectively produced aldehydes and the yield of the isoaldehyde was as high as 98.4% (**1**) (Table 2, entry 5). The selectivity to aldehydes increased with an increase of the π–acceptor properties of the phosphorous ligand. Moreover, the selectivity to aldehydes was affected by temperature and it decreased when the temperature was rising.

The hydroformylation of butyl acrylate carried out at 80 °C with catalyst **I** was not selective and led to a mixture of products composed of 77.6% isoaldehyde (**1**) with 12.2% of the linear aldehyde (the **1**/**2** ratio was 6.4) and 10.2% of the hydrogenation product (Table 2, entry 2). Similarly, in the case of methyl acrylate hydroformylation, the selectivity was also poor, and the main product (51%) was methyl propionate **3**, formed by hydrogenation. In this reaction, the regioselectivity towards the linear aldehyde was better than for butyl acrylate, and the **1**/**2** ratio was 1.1 (Table 2, entry 6).

It is worth noting that the studied catalysts used at room temperature allowed the hydroformylation of butyl acrylate to perform with high selectivity, although the reaction was relatively slow due to the low reactivity of the ester. An increase in temperature accelerated the reaction, however, the selectivity decreased.

Hydroformylation of methyl acrylate worked well with catalyst **I** at room temperature. A rise in temperature resulted in an increase of the hydrogenation efficiency. Catalysts **II** and **III** mainly catalysed the hydrogenation of methyl acrylate even at room temperature.

For comparison, high conversion of up to 95.6% and 69.7% with high regioselectivity to branched aldehydes was achieved

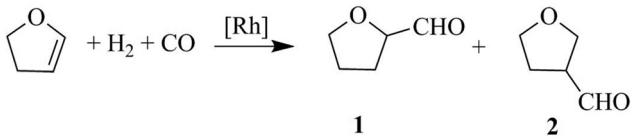


Scheme 2 Hydroformylation of butyl or methyl acrylates.

Table 2 Hydroformylation of butyl and methyl acrylate using catalysts **I**, **II**, and **III** under solventless conditions[a]

Entry	Substrate	Catalyst	t, h	Conv., %	Product distribution 1%[c]	2%[d]	3%	TOF,[e] mol mol^{-1} h^{-1}
1	Butyl acrylate	**I**	12	100	100	0	0	67
2[b]		**I**	1.5	100	77.6	12.2	10.2	479
3		**II**	12	100	97.4	2.6	0	65
4		**III**	12	100	90.4	9.6	0	60
5	Methyl acrylate	**I**	3.5	100	98.4	0	1.6	225
6[b]		**I**	1	100	26	23	51	392
7		**II**	3.5	100	50.2	0	49.8	115
8		**III**	3.5	100	12.5	0	87.5	29

[a] Reaction conditions: substrate (1 ml), [substrate]/[Rh] = 800, P = 20 bar (H_2/CO = 1), T = 25 °C. [b] T = 80 °C. [c] For butyl acrylate, selectivity to 2-methyl-2-oxopropionic acid butyl ester; for methyl acrylate, selectivity to 2-methyl-2-oxopropionic acid methyl ester. [d] For butyl acrylate, selectivity to 4-oxo-butyric acid butyl ester; for methyl acrylate, selectivity to 4-oxo-butyric acid methyl ester. [e] TOF = (mole of product (**1** + **2**))/(mole of catalyst × reaction time).



Scheme 3 Hydroformylation of 2,3-dihydrofuran.

in the hydroformylation of methyl acrylate and butyl acrylate respectively by using a rhodium catalyst with a 2,2′-bis-(dipyrrolylphosphinooxy)-1,1′-(±)-binaphthyl ligand at 20 °C at 2 MPa for 12 h in toluene.[50]

Hydroformylation of 2,3-dihydrofuran

2,3-Dihydrofuran was hydroformylated under solventless conditions with excellent chemoselectivity towards the corresponding aldehydes, namely 2-formyltetrahydrofuran (**1**) and 3-formyltetrahydrofuran (**2**) (Scheme 3).

The results summarized in Table 3 and in Fig. 2 evidenced that catalysts **I**, **II**, and **III** catalysed the hydroformylation of 2,3-dihydrofuran at room temperature, but with different efficiencies.

The best results were obtained for catalyst **I**, which converted 94.8% of the substrate to aldehydes with a **1**/**2** ratio of 3.5, while the conversion decreased to 67.3% with a **1**/**2** ratio of 1.4 when using catalyst **II**. When applying catalyst **III**, a very low conversion, only 7%, was obtained.

The reaction was faster at 80 °C and the three catalysts, **I**, **II**, and **III**, exhibited high catalytic activities and chemoselectivities

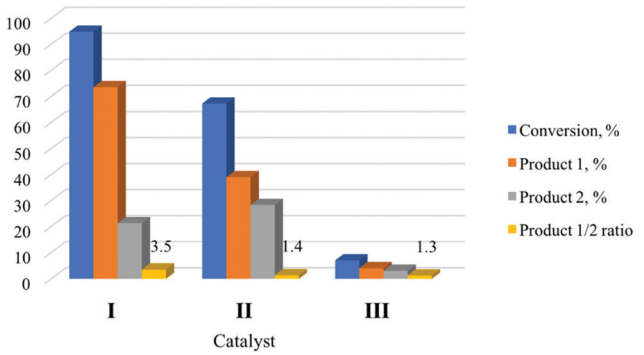


Fig. 2 Hydroformylation of 2,3-dihydrofuran using catalysts **I**, **II**, and **III** at room temperature.

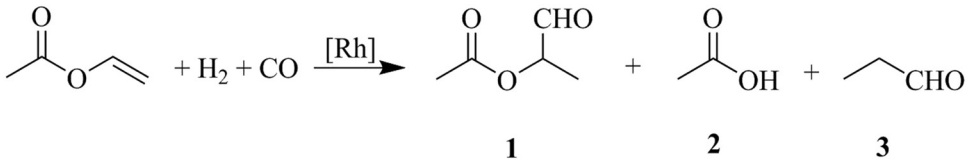
with conversions of 95.3–100% in 1 h. The regioselectivity towards 2-formyltetrahydrofuran (**1**) increased with an increase in the π–acceptor properties of the ligands, and the **1**/**2** ratio was 4.2, 3.3, and 1.7 for **I**, **II**, and **III**, respectively (Table 3, entries 1, 3 and 5).

For comparison, a significantly lower efficiency in the hydroformylation of 2,3-dihydrofuran was reported for rhodium catalysts modified with diphosphite ligands.[16] After 48 h reaction at 45 °C, the conversion of the substrate was 10–45%. Similar regioselectivity towards 2-formyltetrahydrofuran (**1**) was obtained under mild conditions with bisdiazaphospholane ligands (a **1**/**2** ratio up to 3.9).[44] High conversion with a good **1**/**2** ratio up to 1.7 was obtained with a phosphine–phosphoramidite ligand using a substrate to rhodium ratio = 200 in 16 h, while at room temperature a very low conversion was obtained, up to only 8%.[45]

Table 3 Hydroformylation of 2,3-dihydrofuran using catalysts **I**, **II**, and **III** under solventless conditions[a]

Entry	Catalyst	T, °C	t, h	Conv., %	Product distribution 1%[b]	2%[c]	**1**/**2** ratio	TOF,[d] mol mol^{-1} h^{-1}
1	**I**	80	1	95.3	80.8	19.2	4.2	953
2		25	9	94.8	78	22	3.5	105.3
3	**II**	80	1	98	76.5	23.5	3.3	980
4		25	9	67.3	58	42	1.4	74.8
5	**III**	80	1	100	63.5	36.5	1.7	1000
6		25	14	7	57	43	1.3	5

[a] Reaction conditions: substrate (1 ml), [substrate]/[Rh] = 1000, P = 20 bar (H_2/CO = 1), T = 80 °C. [b] Selectivity to 2-formyltetrahydrofuran. [c] Selectivity to 3-formyltetrahydrofuran. [d] TOF = (mole of products (**1** + **2**))/(mole of catalyst × reaction time).



Scheme 4 Hydroformylation of vinyl acetate.

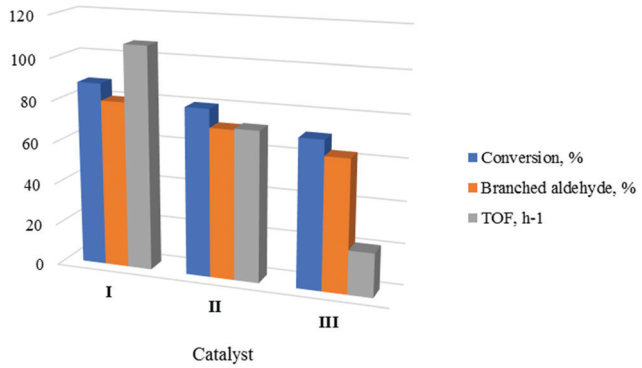


Fig. 3 The effect of the catalyst on the hydroformylation of vinyl acetate at room temperature.

Hydroformylation of vinyl acetate

The hydroformylation of vinyl acetate produced 2-acetoxypropanal (**1**) as a major product, along with acetic acid (**2**) and propanal (**3**) as side products formed by the decomposition of 3-acetoxypropanal (linear aldehyde) (Scheme 4).[36,37]

At room temperature, it is clearly seen that the catalytic activity depends on the kind of *N*-pyrrolyl phosphine coordinated to rhodium (Fig. 3). A decrease in the vinyl acetate conversion, the reaction rate, and the TOF values with a decrease in the number of pyrrolyl groups was observed, in the following order: $HRh(CO)[P(NC_4H_4)_3]_3$ > $HRh(CO)[PhP(NC_4H_4)_2]_3$ > $HRh(CO)[Ph_2P(NC_4H_4)]_3$.

Catalyst **I** is very active and provided total conversion of vinyl acetate in 20 min at 80 °C and in 40 min at 60 °C or 50 °C. A longer time, 4 h, was needed to achieve 100% conversion at 30 °C. It should be pointed out, however, that catalyst **I** converted vinyl acetate to aldehydes at 30 °C and even at 25 °C. The regioselectivity towards the isoaldehyde increased from 82.5 to 89.5% with the temperature lowered from 80 °C to 30 °C, while the TOF decreased from 2000 to 179 mol mol^{-1} h^{-1} (Table 4 and Table S2, ESI†).

At room temperature, the reaction rate with catalysts **II** and **III** was slower, and as a result 80.1% and 70.5% of the substrate was converted in 8 h and 24 h with high regioselectivity towards the isoaldehyde (Table 4, entries 4 and 6). When the temperature was increased to 80 °C, catalysts **II** and **III** showed similar catalytic activity to catalyst **I**. Complete conversion of the substrate was obtained in 20 min at 80 °C with almost the same regioselectivity and TOF (Table 4, entries 3 and 4).

For comparison, the hydroformylation of vinyl acetate without solvent has been reported for rhodium supported on TiO_2 nanotubes; however, a conversion of only 19.5% was reached at 6 MPa.[9] Low conversion, up to 35%, with good chemo- and regioselectivity to the branched aldehyde was obtained by using different ligands at 90–100 °C and 4 MPa of syngas in toluene.[10]

The TOF values of *ca.* 2000 mol mol^{-1} h^{-1} obtained for catalysts **I**, **II**, and **III** at 80 °C exceeded more than twice those reported for vinyl acetate hydroformylation in biphasic systems with water-soluble phosphines at 30 bar.[38] Higher TOF values were achieved with a bulky phosphite ligand $P(ONp)_3$ (tris-1-naphtylphosphite)[39] and with a diphenylphosphinite,[40] under conditions harsher than ours, namely at 4 MPa and 90 °C.

Asymmetric hydroformylation of vinyl acetate

The high catalytic activity of catalysts **I**, **II** and **III** allowed them to be considered as candidates for asymmetric hydroformylation under solventless conditions. In order to achieve asymmetric induction, a chiral ligand, (*R*)-BINAP, was used together with complexes **I**, **II** and **III**.

The effect of (*R*)-BINAP on the reaction course is strongly dependent on its amount (Table 5). At a [(*R*)-BINAP]/[**I**] ratio of 1, complete conversion of vinyl acetate with excellent regioselectivity towards the isoaldehyde was obtained; however, the ee was as low as 1% (Table 5, entry 1). Increasing the [(*R*)-BINAP]/[**I**] ratio to 2 and 3, the reaction rate and conversion decreased to 56 and 41%, but at the same time the enantioselectivity increased to 25 and 44%, respectively (Table 5, entries 2 and 3). A slightly lower ee, 38%, was obtained using

Table 4 Hydroformylation of vinyl acetate using catalyst **I** under solventless conditions[a]

Entry	Catalyst	*T*, °C	*t*	Conv., %	1%[b]	TOF,[c] mol mol^{-1} h^{-1}
1	**I**	80	20 min	100	82.5	2000
2		25	6 h	88	91	107
3	**II**	80	20 min	100	82	1988
4		25	8 h	80	89	72
5	**III**	80	20 min	100	81	1964
6		25	24 h	71	90	21

[a] Reaction conditions: vinyl acetate (1 ml), [substrate]/[Rh] = 800, *P* = 20 bar. [b] Selectivity to 2-acetoxypropanal. [c] TOF = (mole of product **1**)/(mole of catalyst × reaction time).

Table 5 Asymmetric hydroformylation of vinyl acetate using catalyst **I** with the addition of (*R*)-BINAP under solventless conditions

Entry	Catalyst	[L]/[Rh]	Conv., %	1%[b]	ee%	TOF,[c] mol mol^{-1} h^{-1}
1[a]	**I**	1	100	80.4	1	643.2
2		2	56	75	25	74.8
3		3	41	73	44	38.4
4	**II**	3	67	70	23	62.4
5	**III**	3	95.5	76	10	96.1
6	$Rh(acac)(CO)_2$	3	35.8	81	38	38.7
7	$Rh(acac)(CO)_2$ + $P(NC_4H_4)_3$	3	45.8	79	34	48.1

Reaction conditions: vinyl acetate (1 ml), [substrate]/[Rh] = 800, T = 80 °C, P = 20 bar (H_2/CO = 1), L = (*R*)-BINAP, t = 6 h. [a] t = 1 h. [b] Selectivity to 2-acetoxypropanal. [c] TOF = (mole of product **1**)/(mole of catalyst × reaction time).

$Rh(acac)(CO)_2$ with (*R*)-BINAP under the same conditions (Table 5, entry 6). The addition of $P(NC_4H_4)_3$ to this reaction resulted in an increase in the conversion by 10% at a similar ee of 34% (Table 5, entry 7).

For comparison, higher enantioselectivity (an ee of 78%) was reported for the hydroformylation of vinyl acetate with a rhodium catalyst modified with a chiral phosphine–phosphite ligand, however, the reported conversion was only 15%.[41] Bisphosphite chiral ligands, bearing naphthyl substituents, enabled the preparation of a branched aldehyde with an ee from 10 to 26%. The enantioselectivity increased to as much as 99% after the introduction of polyether binders as regulation agents.[42] High enantioselectivity accompanied by excellent regioselectivity and low conversion was obtained using the BettiPhos ligand at a low temperature. Unfortunately, an increase in the reaction temperature led to lower enantioselectivity although the reaction was faster.[49]

Hydroformylation reactions performed with catalysts **II** and **III** and a threefold excess of (*R*)-BINAP were efficient considering the yield of branched aldehyde **1**, however, the enantioselectivity, ee, 23% and 10%, was lower than with catalyst **I** (Table 5, entries 4 and 5). Thus, surprisingly, the non-chiral pyrrolyl phosphine coordinated to the rhodium catalyst affected the reaction enantioselectivity.

The use of BINAP for the rhodium catalysed asymmetric hydroformylation of vinyl acetate resulted in moderate enantioselectivity and yield of the branched aldehyde. On the other hand, this ligand has demonstrated excellent efficiency for asymmetric hydrogenation and isomerisation reactions.[46]

Table 6 Hydroformylation of vinyl acetate under solventless conditions using catalyst $HRh(CO)[P(NC_4H_4)_3]_3$, **I**, modified with chiral ligand (*R*,*R*)-Ph-BPE

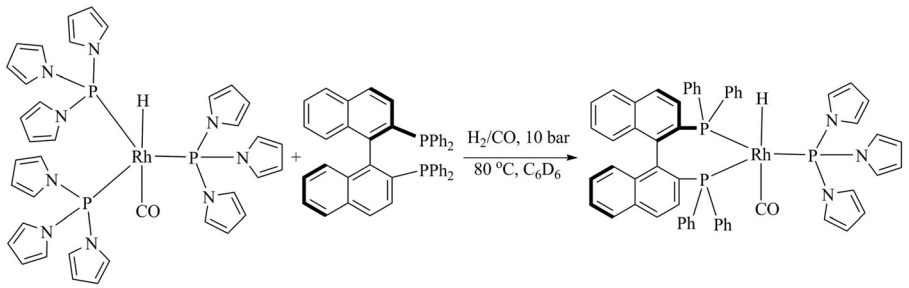
Entry	[L]/[Rh]	Conv., %	1%[d]	ee%	TOF,[e] mol mol^{-1} h^{-1}
1	1.2	96	97	−71	742
2	2	93	98	−81	720
3	3	88	99	−81	696
4[a]	1.2	18	98	−78	136
5[b]	1.2	98	94	−53	736
6[b]	2	98	93	−51	720
7[c]	2	89	99	80	704

Reaction conditions: vinyl acetate (1 ml), [Sub]/[Rh] = 800, P = 20 bar (H_2/CO = 1). T = 80 °C, t = 1 h. [a] T = 60 °C. [b] $Rh(acac)(CO)_2$ as the catalyst. [c] (*S*,*S*)-Ph-BPE. [d] Selectivity to 2-acetoxypropanal. [e] TOF = (mole of product **1**)/(mole of catalyst × reaction time).

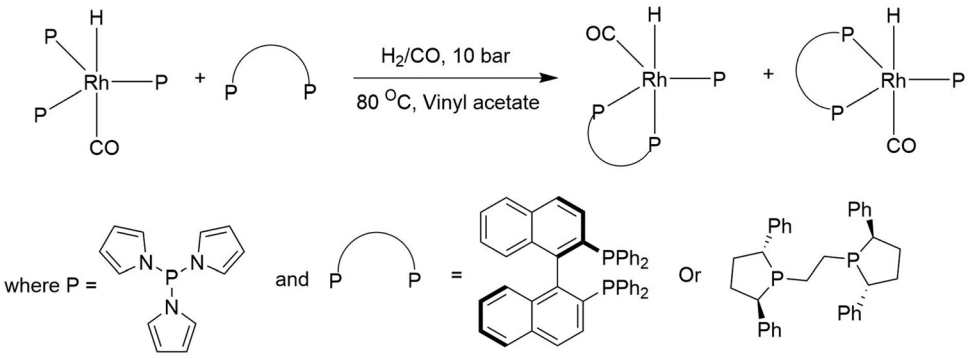
To improve the results of the rhodium catalysed asymmetric hydroformylation of vinyl acetate, (*R*,*R*)-Ph-BPE phosphine was next selected as the chiral ligand.[47,54] A series of reactions were carried out at 60–80 °C and 20 bar of syngas (H_2/CO = 1) with the vinyl acetate to Rh molar ratio varying from 800 to 3000. It was found that the conversion and enantio- and regioselectivities decreased with an increase in the substrate amount and a substrate to Rh ratio equal to 800 was determined to be optimal and used in further studies. The change of the (*R*,*R*)-Ph-BPE to **I** ratio from 1.2 to 2 caused a slight decrease in the vinyl acetate conversion from 96 to 93%, however, the enantioselectivity increased from 71 to 81% (Table 6, entries 1 and 2). Further increases of the ligand amount only affected the conversion, while the enantioselectivity remained the same (Table 6, entry 3). Similarly, high conversion and high enantioselectivity were obtained by using (*S*,*S*)-Ph-BPE (Table 6, entry 7). A significantly lower conversion was obtained when the temperature decreased to 60 °C (Table 6, entry 4). Interestingly, remarkably lower ee values, 53 and 51%, were obtained by utilising $Rh(acac)(CO)_2$ as a catalyst (Table 6, entries 6 and 7). Comparing these results clearly indicated the advantage of catalyst **I** over the *in situ* generated $HRh(CO)_2$(Ph-BPE) in terms of enantioselectivity. While the conversion and TOF values were similar in both catalytic systems, the difference in ee was *ca.* 30% in favour of precursor **I**.

Mechanistic studies

The catalytic results collected for the asymmetric hydroformylation of vinyl acetate indicated the influence of non-chiral pyrrolyl phosphine ligands on the catalytic reaction, in particular on its enantioselectivity. In order to get closer insight into the mechanism of the asymmetric hydroformylation of vinyl acetate, the NMR method was employed. First, the reaction of $HRh(CO)[P(NC_4H_4)_3]_3$ with (*R*)-BINAP was performed in an H_2/CO atmosphere. It was found that (*R*)-BINAP substituted two $P(NC_4H_4)_3$ ligands forming a new hydrido-rhodium complex, with the formula $HRh(CO)[P(NC_4H_4)_3]$(BINAP). As expected, BINAP occupied ee (bisequatorial) positions in a trigonal bipyramidal complex (Scheme 5). This was evidenced by the presence in the ^{31}P NMR of a doublet of triplets in the region of 109 ppm assigned to $P(NC_4H_4)_3$ and a doublet of doublets at 38.15 ppm from two equivalent phosphorus atoms of BINAP (Fig. S12 and S10, ESI†). A similar mixed complex was formed as a product of the partial substitution of PPh_3 in $HRh(CO)(PPh_3)_3$ by a chelating phosphine.[25]



Scheme 5 Reaction of $HRh(CO)(P(NC_4H_4)_3)_3$ with (*R*)-BINAP.



Scheme 6 Reaction of $HRh(CO)[P(NC_4H_4)]_3$ with (*R*)-BINAP or Ph-BPE under hydroformylation conditions.

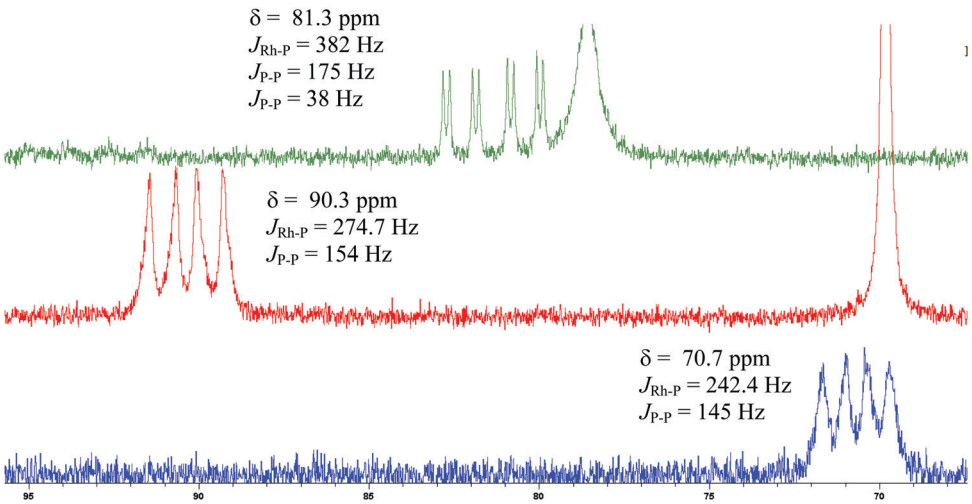


Fig. 4 $^{31}P\{H\}$ NMR spectra in the region of pyrrolyl phosphine measured after vinyl acetate hydroformylation with (*R*)-BINAP and catalysts **I**, **II** and **III** (Fig. S5, S7 and S8 respectively, ESI†).

It is worth noting that the coordination mode ee (bisequatorial) or ea (equatorial–apical) of the chelating phosphine ligand in the catalytic rhodium species has an important influence on the hydroformylation selectivity.[1,43] On the other hand, the exchange of an equatorial and an apical CO ligand is very fast.[25,51]

The next experiment was performed with the same substrates in the presence of vinyl acetate, simulating hydroformylation conditions. The signals assigned to the $P(NC_4H_4)_3$ ligand were shifted to the 80 ppm region and presented two doublets of doublets originating from the coupling with rhodium and with two non-equivalent P atoms of (*R*)-BINAP. The signals assigned to BINAP were observed as two multiplets in the region of 24–28 ppm (Fig. S5, ESI†).

The most interesting finding of these studies is the presence of the $P(NC_4H_4)_3$ ligand in the coordination sphere of rhodium hydride during the entire catalytic process (Scheme 6). The mixed rhodium complex was identified in solution after the hydroformylation of vinyl acetate despite the presence of a threefold excess of (*R*)-BINAP over rhodium (Fig. 4). Our data indicated the presence of three phosphorus atoms bonded to

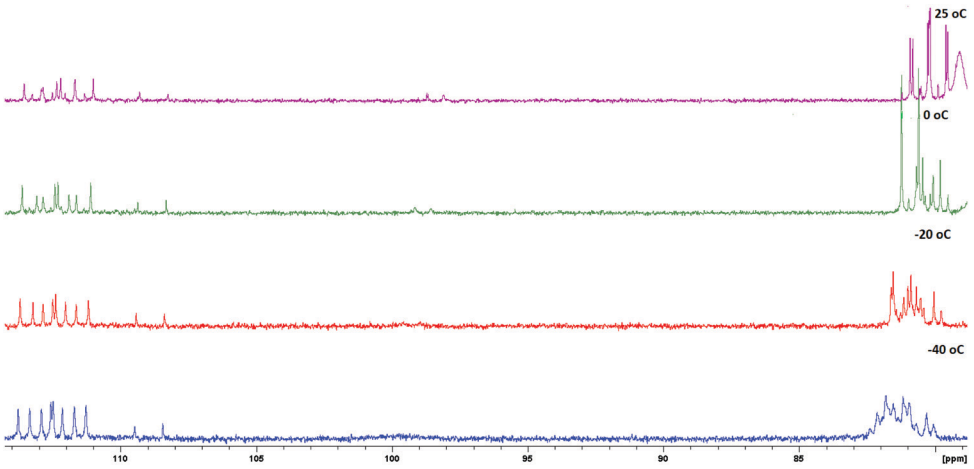


Fig. 5 ^{31}P NMR (toluene-d_8) spectra of the reaction HRh(CO)[P(NC_4H_4)$_3$]$_3$ + (*R*,*R*)Ph-PBE + CO + H_2 at different temperatures.

rhodium in the catalytic process. This is in contrast with the structure of the rhodium hydroformylation catalyst most accepted in the literature, namely the dicarbonyl complex $HRh(CO)_2L_2$ with only two Rh–P bonds.[2]

It is seen in Fig. 4 that under hydroformylation conditions with (*R*)-BINAP, catalysts **II** and **III** presented similar behaviour to catalyst **I**. Due to the dynamic process of ligand exchange, the signals assigned to pyrrolyl phosphines were broadened and only the J_{Rh-P} coupling was observed but not J_{P-P}. On the other hand, the spectra indicated the same coordination mode of (*R*)-BINAP in all three mixed hydrido complexes (Scheme 6). Faster exchange of ligands in the coordination sphere of rhodium facilitated the hydroformylation rate and increased the conversion of vinyl acetate, but decreased the enantioselectivity (Table 5, entries 4 and 5).

The reaction of catalyst **I** with (*R*,*R*)-Ph-BPE was first studied in the absence of H_2/CO. According to ^{31}P NMR, a mixture of different complexes was formed, however, most probably the P(NC_4H_4)$_3$ ligand was completely removed from the coordination sphere of rhodium. The ^{1}H NMR spectrum presented a quintet at $\delta = -10.3$ ppm which can be assigned to HRh[(*R*,*R*)-Ph-BPE]$_2$ (Fig. S28, ESI†). When the same reaction was carried out under H_2/CO, the mixed hydride complex was formed, containing both phosphines. Due to the dynamic processes occurring in the solution, analysis of the ^{31}P NMR spectrum was difficult, however, at lower temperatures the resolution was better (Fig. 5).

For example, at −40 °C, the two doublets of doublets (at δ = 112.5 ppm) originating from diphosphine and two pseudo quartets from P(NC_4H_4)$_3$ (at δ = 81.5 ppm) confirmed the coordination of both phosphines, P(NC_4H_4)$_3$ and (*R*,*R*)-Ph-BPE, to rhodium. Accordingly, the signal of the hydride ligand presented two multiplets at $\delta = -10.84$ ppm. The doublet at δ = 109 ppm (J_{Rh-P} 211 Hz) represents the unreacted precursor **I**.[18] In contrast, rhodium complexes containing only the (*R*,*R*)-Ph-PBE ligand were not detected under these conditions.[52,53]

A similar pattern was also detected in the presence of vinyl acetate, indicating the similar structure of rhodium complexes in both systems with the ee position of the chelating phosphine (Fig. 6). Different coordination modes, in which the Ph-BPE

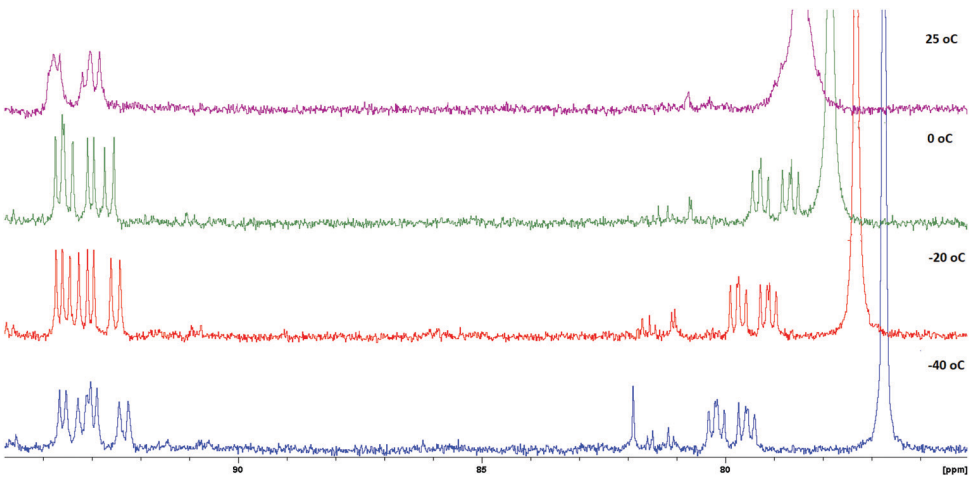


Fig. 6 ^{31}P NMR (toluene-d_8) spectra of the reaction HRh(CO)[P(NC_4H_4)$_3$]$_3$ + (*R*,*R*)-Ph-PBE + CO + H_2 + vinyl acetate at different temperatures.

ligand occupied ea positions in the $HRh(CO)_2$(Ph-BPE) complex, were confirmed by a variable temperature experiment.

The spectroscopic studies supported the observation that both chiral and non-chiral ligands coordinated to rhodium influenced the catalytic activity. In particular, the presence of $P(NC_4H_4)_3$ increased the enantioselectivity originating from Ph-BPE.

Conclusions

Hydrido-rhodium complexes of the type $HRh(CO)L_3$ (where L is an *N*-pyrrolyl phosphine ligand, such as $P(NC_4H_4)_3$, $PPh(NC_4H_4)_2$, or $PPh_2(NC_4H_4)$) were successfully applied in the solventless hydroformylation of unsaturated esters (such as allyl acetate, butyl acrylate, methyl acrylate, or vinyl acetate) and 2,3-dihydrofuran under 20 bar of syngas (H_2/CO = 1) at room temperature. The presence of the pyrrolyl phosphine ligand enabled the selective formation of the desired aldehydes with high efficiency. The strongest π–acceptor phosphine gave the best results, which were remarkably better than those obtained for these substrates in other catalytic systems. As expected, the hydroformylation reactions were faster at 80 °C than at 25 °C. At this temperature, vinyl acetate was hydroformylated with a high reaction rate (TOF up to 2000 mol mol^{-1} h^{-1}), and excellent regioselectivity towards the isoaldehyde.

A moderate enantioselectivity, up to an ee of 44%, was obtained with the addition of a threefold excess of the chiral ligand (*R*)-BINAP in the hydroformylation of vinyl acetate by using catalyst **I**. Excellent chemo- and regioselectivity with high enantioselectivity, up to an ee of 81%, were obtained when another chiral phosphine, (*R*,*R*)-Ph-BPE, was applied.

Spectroscopic studies (^{31}P and ^{1}H NMR) of the reaction mixture revealed the presence of mixed HRh(CO)L(P–P) complexes containing pyrrolyl phosphine (L) and chiral diphosphine (P–P) in both systems. In most catalytic systems used in hydroformylation, $HRh(CO)_2P_2$ species with only two Rh–P bonds have been assumed to be catalytically active.[2] We earlier proposed the presence of three phosphorus atoms in the coordination sphere of rhodium in the active catalysts containing pyrrolyl phosphine ligands.[18] In these studies we shown that the coordination of both ligands to rhodium positively influenced the hydroformylation rate and selectivity. This is especially evident in the hydroformylation of vinyl acetate catalysed by **I** and Ph-BPE, which occurred with much better enantioselectivity than that with a $Rh(acac)(CO)_2$ precursor.

Conflicts of interest

There are no conflicts to declare.

References

1 *Applied Homogenous Catalysis with Organometallic Compounds: A Comprehensive Handbook in Two Volumes*, ed. B. Cornils and W. A. Herrmann, VCH Weinheim, 1996.
2 *Rhodium Catalyzed Hydroformylation*, ed. P. W. N. M. Van Leeuwen and C. Claver, Kluwer Academic Publisher, Dordrecht, 2000.
3 A. M. Trzeciak and J. J. Ziolkowski, *Coord. Chem. Rev.*, 1999, **190–192**, 883–900.
4 *Hydroformylation. Fundamentals, processes and Applications in Organic Syntheses*, ed. A. Börner and R. Franke, Wiley-VCH, Verlag GmbH KGaA, 2016.
5 P. J. Thomas, A. T. Axtell, J. Klosin, W. Peng, C. L. Rand, T. P. Clark, C. R. Landis and K. A. Abboud, *Org. Lett.*, 2007, **9**, 2665–2668.
6 A. G. Panda, P. J. Tambade, Y. P. Patil and B. M. Bhanage, *React. Kinet., Mech. Catal.*, 2010, **99**, 143–148.
7 C. Botteghi, R. Ganzerla, M. Lenarda and G. Moretti, *J. Mol. Catal.*, 1987, **40**, 129–182.
8 C. K. Brown and G. Wilkinson, *J. Chem. Soc. A*, 1970, 2753–2764.
9 Y. Shi, X. Hu, B. Zhu, S. Wang, S. Zhang and W. Huang, *RSC Adv.*, 2014, **4**, 62215–62222.
10 A. A. Dabbawala, R. V. Jasra and H. C. Bajaj, *Catal. Commun.*, 2010, **11**, 616–619.
11 C. F. Hobbs and W. S. Knowles, *J. Org. Chem.*, 1981, **46**, 4422–4427.
12 C. Botteghi, S. Paganelli, A. Schionato and M. Marchetti, *Chirality*, 1991, **3**, 355–369.
13 G. Fremy, Y. Castanet, R. Grzybek, E. Monflier, A. Mortreux, A. M. Trzeciak and J. J. Ziolkowski, *J. Organomet. Chem.*, 1995, **505**, 11–16.
14 A. G. Panda, M. D. Bhor, S. R. Jagtap and B. M. Bhanage, *Appl. Catal., A*, 2008, **347**, 142–147.
15 O. Saidi, S. Liu and J. Xiao, *J. Mol. Catal. A: Chem.*, 2009, **305**, 130–134.
16 A. Gual, C. Godard, S. Castillon and C. Claver, *Adv. Synth. Catal.*, 2010, **352**, 463–477.
17 X. Zheng, K. Xu and X. Zhang, *Tetrahedron Lett.*, 2015, **56**, 1149–1152.
18 A. M. Trzeciak, T. Glowiak, R. Grzybek and J. J. Ziolkowski, *J. Chem. Soc., Dalton Trans.*, 1997, 1831–1838.
19 M. P. Magee, W. Luo and W. H. Hersh, *Organometallics*, 2002, **21**, 362–372.
20 A. M. Trzeciak, B. Borak, Z. Ciunik, J. J. Ziolkowski, C. F. M. Guedes da Silva and L. J. A. Pombeiro, *Eur. J. Inorg. Chem.*, 2004, 1411–1419.
21 A. M. Trzeciak, P. Stepnicka, E. Mieczynska and J. J. Ziolkowski, *J. Organomet. Chem.*, 2005, **690**, 3260–3267.
22 W. Gil, A. M. Trzeciak and J. J. Ziolkowski, *Organometallics*, 2008, **27**, 4131–4138.
23 A. M. Trzeciak, J. J. Ziolkowski and B. Marciniec, *C. R. Acad. Sci., Ser. IIc: Chim.*, 1999, **2**, 235–239.
24 R. Jackstell, H. Klein, M. Beller, K. Wiese and D. Rottger, *Eur. J. Org. Chem.*, 2001, 3871–3877.
25 O. Diebolt, H. Tricas, Z. Freixa and P. W. N. M. Van Leeuwen, *ACS Catal.*, 2013, **3**, 128–137.
26 R. Luo, H. Liang, X. Zheng, H. Fu, M. Yuan, R. Li and H. Chen, *Catal. Commun.*, 2014, **50**, 29–33.
27 X. Zheng, C. Zheng, F. Zhou, H. Fu, M. Yuan, R. Li, B. Xu and H. Chen, *Chin. Chem. Lett.*, 2016, **27**, 678–680.
28 W. Alsalahi, R. Grzybek and A. M. Trzeciak, *Catal. Sci. Technol.*, 2017, **7**, 3097–3103.

29 E. Mieczynska, R. Grzybek and A. M. Trzeciak, *ChemCatChem*, 2018, **10**, 305–310.
30 W. Gil, K. Boczon, A. M. Trzeciak, J. J. Ziolkowski, E. Garcia-Verdugo, S. V. Luis and V. Sans, *J. Mol. Catal. A: Chem.*, 2009, **309**, 131–136.
31 W. Alsalahi and A. M. Trzeciak, *J. Mol. Catal. A: Chem.*, 2015, **408**, 147–151.
32 W. Alsalahi and A. M. Trzeciak, *J. Mol. Catal. A: Chem.*, 2016, **423**, 41–48.
33 M. Zabransky, I. Cisarova, A. M. Trzeciak, W. Alsalahi and P. Stepnicka, *Organometallics*, 2019, **38**, 479–488.
34 Y. S. Varshavsky and T. G. Cherkasova, *Zh. Neorg. Khim.*, 1967, **12**, 1709.
35 K. G. Moloy and J. L. Petersen, *J. Am. Chem. Soc.*, 1995, **117**, 7696–7710.
36 T. Horiuchi, E. Shirakawa, K. Nozaki and H. Takaya, *Organometallics*, 1997, **16**, 2981–2986.
37 W. Alsalahi and A. M. Trzeciak, *ChemistrySelect*, 2018, **3**, 1727–1736.
38 D. Peral, D. Herrera, J. Real, T. Flor and J. C. Bayon, *Catal. Sci. Technol.*, 2016, **6**, 800–808.
39 A. A. Dabbawala, H. C. Bajaj, G. V. S. Rao and S. H. R. Abdi, *Appl. Catal., A*, 2012, **419–420**, 185–193.
40 S. R. Khan and B. M. Bhanage, *Catal. Commun.*, 2014, **46**, 109–112.
41 F. Doro, J. N. H. Reek and P. W. N. M. van Leeuwen, *Organometallics*, 2010, **29**(20), 4440–4447.
42 A. Vidal-Ferran, I. Mon, A. Bauza, A. Frontera and L. Rovira, *Chem. – Eur. J.*, 2015, **21**, 11417–11426.
43 Z. Freixa and P. W. N. M. van Leeuwen, *Dalton Trans.*, 2003, 1890–1901.
44 T. T. Adint, G. W. Wong and C. R. Landis, *J. Org. Chem.*, 2013, **78**(9), 4231–4238.
45 S. H. Chikkali, R. Bellini, B. de Bruin, J. I. van der Vlugt and J. N. H. Reek, *J. Am. Chem. Soc.*, 2012, **134**(15), 6607–6616.
46 C. Claver, M. Dieguez, O. Pamies and S. Castillon, *Top. Organomet. Chem.*, 2006, **18**, 35.
47 A. T. Axtell, J. Klosin and K. A. Abboud, *Organometallics*, 2006, **25**, 5003–5009.
48 C. Cai, S. Yu, B. Cao and X. Zhang, *Chem. – Eur. J.*, 2012, **18**, 9992–9998.
49 C. Schmitz, K. Holthusen, W. Leitner and G. Francio, *ACS Catal.*, 2016, **6**, 1584–1589.
50 X. Shu, H. Liang, Q. Wu, F. Zhou, X. Zheng, H. Fu, B. Xu, R. Li, C. Zhang and H. Chen, *RSC Adv.*, 2017, **7**, 14816–14823.
51 S. van der Slot, P. C. J. Kamer, P. W. N. M. van Leeuwen and B. T. Heaton, *Organometallics*, 2001, **20**, 430–441.
52 D. Crozet, A. Gual, D. McKay, C. Dinoi, C. Godard, M. Urrutigoïty, J.-C. Daran, L. Maron, C. Claver and P. Kalck, *Chem. – Eur. J.*, 2012, **18**, 7128–7140.
53 D. Crozet, D. McKay, C. Bijani, A. Gual, C. Godard, C. Claver, L. Maron, M. Urrutigoïty and P. Kalck, *Dalton Trans.*, 2012, **41**, 3369–3373.
54 A. T. Axtell, J. Klosin, G. T. Whiteker, C. J. Cobley, M. E. Fox, M. Jackson and K. A. Abboud, *Organometallics*, 2009, **28**, 2993–2999.