N-Pyrolylphosphines as ligands for highly regioselective rhodium-catalyzed 1-butene hydroformylation: effect of water on the reaction selectivity†

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The hydroformylation of 1-butene catalyzed by Rh(acac)(CO)2 with an excess of N-pyrrolylphosphine ligands, L = P(NC3H4)3, PPh3(NC4H4) or PPh(NC5H6)2, was investigated under constant pressure of synthesis gas (4–10 bar, H2/CO = 1) and 2 bar of 1-butene at temperatures ranging from 50 to 80 °C. N-Pyrolylphosphine ligands facilitated excellent selectivity towards aldehydes and regioselectivity towards linear aldehydes. The application of a higher temperature, the presence of a small amount of water, and a [L]/[Rh] ratio of ca. 13 resulted in the achievement of the highest n/iso values in a short time. A further increase in selectivity was achieved after the addition of water to the reaction mixture. The catalytic performance of the studied systems showed an increase in selectivity (n/iso) with the increase of the number of pyrrol groups in phosphine: (P(NC4H4)3 > PPh(NC4H4)2 > PPh2(NC5H6)) > PPh3.

1. Introduction

The olefin hydroformylation reaction (also known as the oxo synthesis or Roelen’s reaction) is the oldest, largest, and most important homogeneously catalyzed industrial process for the production of aldehydes. This reaction was accidentally discovered by Otto Roelen in 1938 at Ruhrchemie, Germany, while he was studying the cobalt-catalyzed Fischer-Tropsch reaction.

Today rhodium is a metal of choice in industrial installations which produce mainly C4 aldehydes by the conversion of propylene. To achieve a high yield and selectivity towards aldehydes, the rhodium precursor should be modified by applying a ligand (preferably phosphorus), in high excess with respect to the metal.1–9 Several factors are used to characterize the activity of the catalytic system, such as the turnover number (TON), turnover frequency (TOF), yield, reaction rate, selectivity, and n/iso ratio.10

N-Valeraldehyde, manufactured by the hydroformylation of 1-butene, is used as a chemical building block in the production of amyl alcohol (n-pentanol) and valeric acid. It is also employed as a flavoring, a fragrance additive, a rubber accelerator, and in resin chemistry.11,12

The catalytic system composed of Rh(acac)(CO)2 and an N-pyrrolylphosphine ligand exhibited high regioselectivity towards linear aldehydes in the hydroformylation of 1-hexene and vinylsilanes.10 The results were significantly better than when Rh(acac)(CO)2 was applied with an excess of PPh3. During the reaction, rhodium hydrido complexes containing pyrolylphosphine ligands of the type HRh[PPh3(NC4H4)]2-14 (x = 0–2) and HRh(CO)[PPh3(NC5H4)]2-15 were identified as catalytically active species. These complexes also exhibited good catalytic activity in the hydrogenation of olefins and arenes.13

Jackstell et al. applied the same catalytic system in the hydroformylation of 2-pentene at a high pressure (50 bar) and 120 °C with an [L]/[Rh] ratio of 100. A good n/iso ratio was also obtained at a low pressure of syngas (10 bar) with a P(NC4H4) ligand.14 van Leeuwen et al. demonstrated the high activity (TOF) and excellent selectivity of ethene hydroformylation in the presence of P(NC4H4).15 Similarly, Luo et al. reported high selectivity towards dialdehydes in the hydroformylation of dicyclopentadiene in the presence of P(NC4H4).16 The same system was used by Zheng et al. and it exhibited a high activity in the hydroformylation of α-methylstyrene and enhanced regioselectivity towards the linear aldehydes (99%) with a high TOF (5786 h−1) under mild conditions (syngas pressure of 6 MPa, 110 °C).17 In contrast, Breit used the P(NC4H4)3 phosphate for the hydroformylation of styrene with low conversion and poor regioselectivity.18 A good
regioselectivity and high activity has been achieved in rhodium catalyzed hydroformylation of 1-octene with bidentate N-arylphosphine.\textsuperscript{19}

In this paper, we present the application of rhodium systems modified by N-arylphosphines in the hydroformylation of 1-butene in toluene and in a toluene-water mixture. These systems showed a high regioselectivity towards n-valeraldehyde, in most cases higher than with the use of PPh\textsubscript{3}.

2. Experimental

2.1. Materials

The rhodium complex Rh(acac)(CO)\textsubscript{2} was synthesized according to the literature.\textsuperscript{20} The N-arylphosphine ligands P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3}, PPh(NC\textsubscript{4}H\textsubscript{4})\textsubscript{2}, and PPh\textsubscript{2}(NC\textsubscript{4}H\textsubscript{4}) were synthesized as described in the literature.\textsuperscript{21} Triphenylphosphine (PPh\textsubscript{3}) was purchased from Avocado; 1-butene was purchased from Air Liquide; hydrogen (H\textsubscript{2}, 99.999\%) and carbon monoxide (CO, 99.97\%) were procured from Air Products.

2.2. Synthesis of HRh(CO)(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3})\textsubscript{3} and HRh(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{4})\textsubscript{4}

The synthesis of HRh(CO)(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3})\textsubscript{3} and HRh(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{4})\textsubscript{4} was performed in a stainless autoclave (50 ml) under pressure of syngas (H\textsubscript{2}/CO = 1) and hydrogen, respectively. In a typical synthesis, Rh(acac)(CO)\textsubscript{2}, P(NC\textsubscript{4}H\textsubscript{4}), and toluene were introduced into the autoclave under a nitrogen atmosphere (Table 1), the autoclave was closed and flushed with H\textsubscript{2} (5 bar) three times, and thereafter pressurized with syngas (H\textsubscript{2}/CO = 1) or hydrogen, heated to 80 °C and stirred for 1 h.

3. Results and discussion

The hydroformylation of 1-butene catalyzed by four catalytic systems containing the catalyst precursor Rh(acac)(CO)\textsubscript{2} with a 13-fold excess of N-arylphosphine, P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3}, PPh(NC\textsubscript{4}H\textsubscript{4})\textsubscript{2}, PPh\textsubscript{2}(NC\textsubscript{4}H\textsubscript{4}), or triphenylphosphine PPh\textsubscript{3}, was first investigated in toluene. Aldehydes were formed as the main reaction products, namely 1-pentanal (a linear aldehyde) and 2-methylbutanal (a branched aldehyde) together with small amounts of 2-butene (isomerization product) (Scheme 1).

The results presented in Table 2 and in Fig. S1\textsuperscript{†} illustrate the effect of temperature increase from 50 °C to 80 °C on the hydroformylation of 1-butene catalyzed by the catalytic system Rh(acac)(CO)\textsubscript{2} + PPh\textsubscript{3}(NC\textsubscript{4}H\textsubscript{4}) with 2 bar of 1-butene and 10 bar of the synthesis gas (H\textsubscript{2}/CO = 1). An increase in the yield of aldehydes was observed with an increase in the temperature. Thus, when the temperature was raised from 50 to 80 °C, the n/iso ratio increased from 8.2 to 11.2. The TOF values also increased.

Much better results, in particular a higher rate and higher selectivity, were obtained in reactions performed with the addition of water to the reaction mixture. Thus, an increase in the water amount from 0.5 to 2 mL caused a remarkable increase in the n/iso ratio with a maximum value of 16.2. However, the TOF decreased during the same time from 800 to 667 h\textsuperscript{−1} (Table 3, Fig. S2\textsuperscript{†}). This is in agreement with our previous observation that regioselectivity was higher in the presence of water in a reaction mixture.\textsuperscript{22,23} However, in contrast to other olefins,\textsuperscript{22} the hydroformylation of 1-butene only in water was not successful because aldehydes were not formed.

The effect of time was also studied in the catalytic system Rh(acac)(CO)\textsubscript{2} + PPh\textsubscript{3}(NC\textsubscript{4}H\textsubscript{4}) at 80 °C (Table 4). The results showed an increase in the yield of aldehydes with the prolongation of the reaction time. However, simultaneously, n/iso also increased from 14.5 after a short time (4 min) (Table 3, entry 1) to 19.1 and 19.7 after 6 and 8 min of reaction time, respectively (Table 3, entries 2 and 3). Then, the n/iso ratio decreased to ca. 14 again. Fig. S3\textsuperscript{†} displays the effect of time

| Complex              | Rh(acac)(CO)\textsubscript{2} | P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3} | P, bar | Yield   |
|----------------------|--------------------------------|----------------------------------------------------------|--------|---------|
| HRh(CO)(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3})\textsubscript{3} | 0.078 g | 0.24 g | 10 bar of syngas (H\textsubscript{2}/CO = 1) | 0.18 g  |
| HRh(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{4})\textsubscript{4} | 0.054 g | 0.25 g | 5 bar of H\textsubscript{2} | 0.083 g  |

\textsuperscript{a} Reaction conditions: toluene as the solvent (3 ml), 80 °C, 1 h. \textsuperscript{b} 0.05 g of HRh(CO)(P(NC\textsubscript{4}H\textsubscript{4})\textsubscript{3})\textsubscript{3} was also formed.
The effect of the $\text{[PPh}_2\text{NC}_4\text{H}_4\text{]}/\text{[Rh]}$ ratio on the reaction course was studied in the range from 2 to 13 at 80 °C and 10 bar. The results listed in Table 5 and in Fig. S4† show that, as the $\text{[PPh}_2\text{NC}_4\text{H}_4\text{]}/\text{[Rh]}$ ratio increased from 2 to 13, the $n$/iso ratio increased from 2.1 to 11.2. While selectivity increased in parallel with the amount of the phosphorus ligand; the highest TOF value was achieved at $[\text{L}]/[\text{Rh}] = 6$. A further increase in the PPh$_2$(NC$_4$H$_4$) amount caused a decrease in the TOF.

Applying the optimized reaction conditions, we tested three other catalytic systems composed of Rh(acac)(CO)$_3$ and P(NC$_4$H$_4$)$_3$, PPh(NC$_4$H$_4$)$_2$ or PPh$_3$ (Table 6). It should be underlined that regioselectivity to $n$-pentanal was very high in both systems containing P(NC$_4$H$_4$)$_3$ or PPh(NC$_4$H$_4$)$_2$ ligands. An excellent conversion and lower regioselectivity were obtained by utilizing PPh$_3$. On the other hand, a remarkable
increase in the n/iso ratio was achieved after addition of water to the reaction media. It is also worth noting that the n/iso ratio increased with the increase in the number of pyrrolyl groups present in phosphine. It means that the n/iso ratio decreased in the following order: P1-NC4H4)3 > PPh1-NC4H4)2 > PPh2-NC4H4) > PPh3 (Scheme 2).

Fig. S5† shows an increase of hydroformylation selectivity achieved by addition of water to the reaction mixture. The effect was noted for all studied phosphines; however, it was most pronounced for the best π-acceptor one, P1-NC4H4)3.

It should be noted that the yield of aldehydes increased with an increase in the autoclave volume. It was demonstrated for the Rh(acac)(CO)2 + PPh3 system (Table 7). The yields of aldehydes were 0.022 and 0.013 mol in reactions carried out using 100 and 50 mL autoclaves, respectively, and 2 mL of toluene (Table 7). The n/iso ratio was, however, almost the same.

Considering the fact that a higher yield of aldehydes could be obtained in a larger-volume autoclave, the effect of the total pressure of the syngas (H2 : CO = 1 : 1) on the catalytic activity and regioselectivity towards the linear aldehyde was studied using a 100 mL autoclave. The results obtained at 4–10 bar and 80 °C for 2 h employing the catalytic systems [Rh(acac)(CO)2/P(NC4H4)3, PPh(NC4H4)2, or PPh2(NC4H4)] are shown in Table 8. Thus, the effect of pressure on the catalytic activity of the three systems and the amount of aldehydes decreased when the pressure of the syngas decreased from 10 to 4 bar. The n/iso ratio was affected differently, greatly increasing with a pressure decrease from 10 to 6 bar and then starting to decrease at 4 bar. As a result, the highest

Table 5 Effect of the [L]/[Rh] ratio on 1-butene hydroformylation

| Entry | [L]/[Rh] | Conv. (%) | Aldehydes, mol | n/iso | TOF, mol mol⁻¹ h⁻¹ |
|-------|----------|-----------|----------------|-------|-------------------|
| 1     | 2        | 83.2      | 0.008          | 2.1   | 533               |
| 2     | 4        | 91.7      | 0.010          | 2.4   | 667               |
| 3     | 6        | 96.7      | 0.011          | 4.3   | 733               |
| 4     | 8        | 95.2      | 0.010          | 7.2   | 667               |
| 5     | 10       | 96.6      | 0.010          | 8.9   | 667               |
| 6     | 13       | 95.0      | 0.010          | 11.2  | 667               |

Reaction conditions: [Rh] = 1.5 × 10⁻⁵ mol, PPh2(NC4H4) as the ligand, P1-butene = 2 bar, P(H2:CO=1:1) = 10 bar, toluene (0.5 mL), cyclohexane (0.25 mL), t = 1 h, T = 80 °C. Conversion of 1-butene was calculated according to GC-FID analyses of the post-reaction mixture. The TOF values were calculated as moles of the aldehyde/[moles of the catalyst] × reaction time.

Table 6 Results of 1-butene hydroformylation using P(NC4H4)3, PPh(NC4H4)2 and PPh3 as modifying ligands

| Entry | L             | Conv. (%) | Aldehydes, mol | n/iso | TOF, mol mol⁻¹ h⁻¹ |
|-------|---------------|-----------|----------------|-------|-------------------|
| 1     | P(NC4H4)3     | 80.2      | 0.007          | 18.6  | 467               |
| 2     | PPh(NC4H4)2   | 85.8      | 0.0082         | 23.1  | 547               |
| 3     | PPh(NC4H4)2   | 88.0      | 0.009          | 15.4  | 600               |
| 4     | PPh(NC4H4)2   | 88.5      | 0.009          | 18.2  | 600               |
| 5     | PPh3          | 96.8      | 0.0132         | 5.8   | 880               |
| 6     | PPh3          | 94.5      | 0.0129         | 7.9   | 860               |

Reaction conditions: [Rh] = 1.5 × 10⁻⁵ mol, [L]/[Rh] = 13, P1-butene = 2 bar, P(H2:CO=1:1) = 10 bar, toluene (0.5 mL), cyclohexane (0.25 mL), t = 1 h, T = 80 °C. Water (0.5 mL). Conversion of 1-butene was calculated according to GC-FID analyses of the post-reaction mixture. The TOF values were calculated as moles of the aldehyde/[moles of the catalyst] × reaction time.

Scheme 2 The impact of the P ligand on the activity and the n/iso ratio.
selectivity (n/iso) was achieved at 6 bar, whereas for P(NC₅H₁₅)₃ the maximum was reached at 8 bar. Addition of water caused a significant increase in regioselectivity, and the n/iso ratio reached 50.9 at 6 bar using P(NC₅H₁₅)₃ (Table 8, entry 5). The positive effect of water was also evidenced for other phosphines (Fig. 1).

The ³¹P NMR spectra measured after the hydroformylation of 1-butene showed evidence of rhodium species formed during the catalytic reaction. Catalytically active hydrido-carbonyl rhodium species [RhH(CO)L₃] were formed in the reactions of Rh(acac)(CO)₂ with an excess of N-pyrrolylphosphine ligands during hydroformylation. As shown in Table 9, the ³¹P-NMR data of the reaction products are in agreement with those reported earlier.⁹¹³

The effect of water on hydroformylation of 1-butene was also studied by utilizing HRh(CO)(P(NC₅H₁₅)₃ and HRh[P(NC₅H₁₅)₃] complexes as catalysts. In the absence of an added ligand, HRh(CO)(P(NC₅H₁₅)₃ exhibited high catalytic activity in both reaction media, namely toluene and the water–toluene mixture. Conversion and selectivity were almost the same in both system; however, the n/iso ratio was slightly higher in a water–toluene mixture (Table 10, entries 1 and 2). Addition of 3-fold excess of the P(NC₅H₁₅)₃ ligand increased the n/iso ratio to 4 and 4.8, respectively (Table 10, entries 3 and 4). The reaction rate and conversion decreased at 13-fold excess of P(NC₅H₁₅)₃ with a significant increase in regioselectivity towards the linear aldehyde. Thus, the n/iso ratio

### Table 7 Hydroformylation of 1-butene using PPh₃ as the ligand

| Entry | Toluene, mL | Conv. b | Aldehydes, mol | n/iso | TOF c, h⁻¹ |
|-------|-------------|---------|----------------|-------|-------------|
| 1     | 2           | 97      | 0.022          | 3.6   | 733         |
| 2     | 2           | 95      | 0.013          | 3.8   | 867         |

Reaction conditions: [Rh] = 1.5 × 10⁻⁵ mol, PPh₃ as the ligand, [L]/[Rh] = 13, P₁-Butene = 2 bar, P(H₂:CO=1:1) = 10 bar, cyclohexane (0.25 mL), t = 1 h, T = 80 °C. a Autoclave 100 mL, t = 2 h. b Conversion of 1-butene was calculated according to GC-FID analyses of the post-reaction mixture. c The TOF values were calculated as moles of the aldehyde/moles of the catalyst × reaction time.

### Table 8 Effect of the CO/H₂ pressure on hydroformylation of 1-butene catalyzed by Rh(acac)(CO)₂ modified with different ligands

| Entry | Ligand | P, bar | Conv. b | Aldehydes, mol | n/iso | TOF c, mol mol⁻¹ h⁻¹ |
|-------|--------|--------|---------|----------------|-------|---------------------|
| 1     | P(NC₅H₁₅)₃ | 10     | 93.0    | 0.019          | 18.0  | 633                 |
| 2     | 8      | 80.0   | 0.014   | 21.7           | 437   |
| 3     | 6      | 84.9   | 0.013   | 46.2           | 300   |
| 4     | 4      | 78.2   | 0.009   | 16.5           | 367   |
| 5     | 2      | 80.8   | 0.011   | 50.9           | 367   |
| 6     | 4      | 84.5   | 0.004   | 17.8           | 133   |
| 7     | PPh(NC₅H₁₅)₂ | 10   | 96.0    | 0.021          | 11.2  | 700                 |
| 8     | 8      | 94.0   | 0.018   | 22.5           | 600   |
| 9     | 6      | 90.7   | 0.017   | 26.8           | 563   |
| 10    | 4      | 93.2   | 0.017   | 24.2           | 563   |
| 11    | 8      | 81.5   | 0.011   | 31.2           | 367   |
| 12    | 4      | 68.8   | 0.007   | 20.0           | 233   |
| 13    | PPh₃(NC₅H₁₅) | 10  | 94.2    | 0.018          | 5.2   | 600                 |
| 14    | 8      | 93.6   | 0.020   | 8.2            | 667   |
| 15    | 6      | 86.2   | 0.016   | 14.8           | 533.3 |
| 16    | 4      | 86.8   | 0.017   | 13.3           | 567   |
| 17    | 2      | 88.6   | 0.017   | 17.9           | 567   |
| 18    | 4      | 47.0   | 0.004   | 7.3            | 133   |

Reaction conditions: [Rh] = 1.5 × 10⁻⁵ mol, [L]/[Rh] = 13, P₁-Butene = 2 bar, P(H₂:CO=1:1) = 4–10 bar, toluene (0.5 mL), cyclohexane (0.25 mL), t = 2 h, T = 80 °C. a Water (0.5 mL). b Conversion of 1-butene was calculated according to GC-FID analyses of the post-reaction mixture. c The TOF values were calculated as moles of the aldehyde/moles of the catalyst × reaction time.

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![Fig. 1](image-url) **Fig. 1** Effect of water and pressure on 1-butene hydroformylation catalyzed by Rh(acac)(CO)₂ modified with different ligands at 80 °C in a 100 mL autoclave.
increased from 19.7 to 31.3 (Table 10, entries 5 and 6). The unmodified HRh[P(NC₆H₄)₃]₄ catalyst also displayed a higher n/iso ratio after the addition of water to the reaction (Table 10, entries 7 and 8).

### 4. Conclusions

The hydroformylation of 1-butene catalyzed by Rh(acac)(CO)₂ with an excess of N-pyrolylphosphine and PPh₃ ligands at 50–80 °C and 4–10 bar of syngas (H₂:CO = 1:1) in toluene and in a toluene/water mixture was investigated. Hydrido-carbonyl rhodium species were formed in situ during the hydroformylation. Regioselectivity towards the linear aldehyde increased with the increase in the number of the pyrrolyl groups in phosphine ligands. At the same time, the reaction rate decreased in the same order. Thus, better π-acceptor properties of the ligand promote the increase in the n/iso ratio.

Regioselectivity is highly dependent on the reaction conditions, such as temperature or the [L]/[Rh] molar ratio. In addition, remarkably high regioselectivity towards the linear aldehyde was noted in a shorter reaction time or at a lower syngas pressure.

Interestingly, a similar effect, namely a selectivity increase, was also observed after the introduction of water to the reaction mixture. Moreover, an increase in the n/iso ratio was in this case dependent on the kind of phosphine used. It can be, therefore, assumed that water interacted with the hydrido-olefin rhodium intermediate facilitating the formation of the linear alkyl complex in the migratory insertion step. The effect of water on the increase in the n/iso ratio was most clearly pronounced for the P(NC₆H₄)₃ ligand, suggesting an important role of N atoms in the formation of hydrogen bonds. Such an interaction caused the decrease in the electron density on the rhodium center, which is then reflected in the migratory insertion step (Scheme 3) leading
to the anti-Markovnikov (linear) product. In summary, we suppose that selectivity of hydroformylation increased because π-acceptor properties of P-ligands were further enhanced by interactions with water molecules.

However, interactions of water with the hydride ligand or with coordinated olefin could be also considered. Water can also facilitate the formation of rhodium hydride, which is catalytically active. It is possible that water enhances the hydride transfer step.\(^{24}\)

According to the well accepted scheme of hydroformylation, based on theoretical calculations published till now, the insertion step is the rate-determining step for hydroformylation regioselectivity.\(^{25-28}\) Thus, stabilization of the transition state leading to the linear Rh-alkyl intermediate results in an increase in the linear aldehyde amount and, consequently, in a higher \(n/\text{iso}\) ratio. This is observed in the presence of water in our system. It could be therefore proposed that nonbonding interactions of water molecules with phosphines, olefin and the hydride ligand present in the coordination sphere of rhodium decrease the activation energy of the transition state leading to the linear Rh-alkyl intermediate. In this way, the reaction pathway that leads to the linear aldehyde is favored. This hypothesis, based on experimental results, should be verified by theoretical calculations which are in progress.

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