Preparation of a Series of Supported Nonsymmetrical PNP-Pincer Ligands and the Application in Ester Hydrogenation

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Abstract: In contrast to their symmetrical analogues, nonsymmetrical PNP-type ligand motifs have been less investigated despite the modular pincer structure. However, the introduction of mixed phosphorus donor moieties provides access to a larger variety of PNP ligands. Herein, a facile solid-phase synthesis approach towards a diverse PNP-pincer ligand library of 14 members is reported. Contrary to often challenging workup procedures in solution-phase, only simple workup steps are required. The corresponding supported ruthenium-PNP catalysts are screened in ester hydrogenation. Usually, industrially applied heterogeneous catalysts require harsh conditions in this reaction (250–350 °C at 100–200 bar) often leading to reduced selectivities. Heterogenized reusable Ru-PNP catalysts are capable of reducing esters and lactones selectively under mild conditions.

Introduction

Terdentate pincer-type ligands have attracted tremendous attention for applications in a broad range of catalytic reactions since the pioneering work of Shaw and van Koten in the 1970s.[1] Given that the modular nature of pincer ligands allows for efficient fine-tuning of the electronic and steric properties,[2] symmetrical PNP pincer ligands, which feature a central N-donor and two identical phosphorus moieties, have been studied extensively in the last two decades. Although nonsymmetrical PNP ligands give access to a significantly increased number of potential ligand structures with unique stereo-electronic properties, reports remain fairly limited.[3] This can be attributed to the often more challenging synthesis and troublesome purification procedures required for nonsymmetrical pincers opposed to simplified twofold-substitution protocols for ligands with $C_2$v symmetry. In case of representative chiral PNP pincers I–V, ligand desymmetrization was achieved through additional substituents in the aliphatic backbone as well as through mixed phosphorus-donor moieties (Figure 1).[4]

To the best of our knowledge, ligands VI–IX reported by Kinoshita et al. remain the sole examples of nonsymmetrical pyridine-based PNP ligands which differ in the nature of the phosphines.[5] Structures VI–IX, composed of a P(tBu)2 group and a second P-donor bearing alkyl and aryl substituents, were prepared by successive deprotonation and mono-substitution of 2,6-lutidine using various chlorophosphines.

Regardless of the advances in rational design of high-performance ligands, synthetic approaches through trial-and-error remain the most common methodologies for catalyst optimization. There is, however, still a lack of efficient combinatorial methods enabling the synthesis and screening of large ligand libraries, especially for phosphorus-based multidentate ligands.[6]

Although modular approaches towards symmetrical pyridine-based PNP pincer ligands have been explored by Kirchner and co-workers,[7] facile synthetic protocols towards large combinatorial ligand libraries of nonsymmetrical PNP-type ligands remain elusive.

Solid-phase synthesis (SPS), originating from well-established polypeptide synthesis, offers an attractive alternative tool towards ligand libraries.[8] The main advantage of SPS over traditional solution-phase approaches is the ease of purification, often requiring only a simple filtration step and allowing for
the use of a large excess of reactants. Systematic variation of substituents bound to the phosphine moieties enables the preparation of a large combinatorial PNP ligand library through SPS. This facilitates the finetuning of ligand properties for catalyst optimization.

Moreover, catalyst immobilization on insoluble supports combines the advantages of both worlds, that is, high activity, selectivity and tunability of homogeneous catalysts and the recoverability and recyclability of heterogeneous catalysts. In particular, the recycling of these expensive and often toxic transition metals and ligands can be truly simplified.

Notwithstanding the wide applicability of PNP pincer-based catalysts, approaches towards immobilization strategies remain fairly limited. Goni et al. reported on a Ru-PONOP-type catalyst supported on a silica poly(allylamine) composite through a two-step Mannich reaction yielding two regioisomers covalently bound to the solid in both ortho- and meta-position of the central pyridine ring. Similarly, a phosphine oxide PNP ligand was anchored onto mesoporous silica through a Cu-catalyzed click reaction by Lo et al. Upon reduction to the free supported phosphine, the corresponding Ir-PNP catalyst was applied in CO hydrogenation. Wang et al. employed a “knitting” strategy by anchoring a solution-phase Ru-PNP catalyst covalently to the structure of a porous organic polymer for application in dehydrogenation of formic acid. A supported ionic-liquid phase (SILP) strategy was chosen by the group of Kirchner for the immobilization of a Fe-PNP catalyst in ionic liquids deposited on both silica and polymer-based spherical activated carbon. However, in all cases a single premade PNP ligand or complex is immobilized missing the opportunity for efficient ligand modification. This calls for a more versatile and combinatorial methodology that allows for the facile synthesis of a diverse PNP-ligand library.

Pincer ligands have contributed tremendously to environmentally benign, homogeneously catalyzed reductions employing molecular hydrogen as an atom-economical reducing agent. Particularly, challenging hydrogenations of carboxylic acids and their ester derivatives represent crucial transformations in organic synthesis for both laboratory scale as well as bulk and fine-chemical industry. Common synthetic methods often rely on the use of stoichiometric amounts of metal hydrides such as LiAlH₄ and NaBH₄ which is accompanied by the hazard in handling as well as the generation of large amounts of inorganic waste. In industrial applications, heterogeneous catalysts require harsh reaction conditions (250–350 °C at 100–200 bar) often leading to side-product formation and limited functional-group tolerance. Consequently, there has been a strong drive from both academia and industry to develop molecularly well-defined homogeneous catalysts for selective catalytic hydrogenations under milder conditions (see representative examples in Figure 2).

Since Milstein’s seminal work on the non-innocent pyridine-based PNN ligand in Ru-catalyzed ester hydrogenation, a plethora of pincer-type catalysts has been developed. In contrast to their nonsymmetrical PNN analogue, Ru-PNN catalysts (XI and XII) employing symmetrical PNP ligands exhibited significantly less activity in this transformation. This was associated with the lack of hemilability of one of the side arms due to two equally strong electron-donating phosphorus moieties present in both ligands. As an alternative to the pyridine backbone, aliphatic PNP(H) ligands employed in catalysts such as Ru-MACHO (XIII) but also base-metal catalysts have demonstrated excellent performances in the reduction of esters. Inspired by the highly active Ru-SNS (XIV) and Ru-PNN (XV) ester hydrogenation catalysts developed by Gusev and co-workers, we recently reported on the first reusable, rebinding Ru-PNN system (XVI) applicable in this reaction under very mild conditions (25 °C, 50 bar).

In this work, we demonstrate the first synthesis of a supported combinatorial library of nonsymmetrical pyridine-based PNP ligands by using a facile solid-phase synthesis approach. Moreover, the application of the corresponding heterogeneous Ru-PNP catalysts in the hydrogenation of various lactones, mono-, and diesters is reported.

Results and Discussion

The PN building blocks 1a–h were prepared by adapting a procedure reported by Gargir et al. (Scheme 1). 2,6-Bis(chloromethyl)pyridine was treated with 1.0 equivalent of freshly prepared lithium boranyl phosphanides bearing combinations of substituents R² and R³ attached to the phosphorus moiety. A series of both aromatic (Ph, 4-MeOPh, 4-CF₃Ph, 1a–c) and alkyl-based substituents (Cy, iBu, tBu, Ad, 1d–f and 1h) were employed as well as a phosphine–borane with mixed substituents (Ph and tBu, 1g).

The systematic variation of R² and R³ enables an efficient tuning of the steric and electronic properties of the phospho-

![Figure 2. Representative examples of pincer-based ruthenium catalysts used in ester hydrogenation.](image)

![Scheme 1. Synthesis of PN building blocks 1a–h.](image)
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The preparation of phosphine–boranes 2a–d immobilized on Merrifield resin cross-linked with 1% divinylbenzene (DVB, MF 1%, n = 1, 2a and 2c), Merrifield resin cross-linked with 4% DVB (MF 4%, n = 1, 2b) and polystyrene (PS, n = 0, 2d) were prepared as previously reported by our group. Treatment of 2a–d with an excess of potassium bis(trimethylsilyl)amide (KHMDS) yielded the deprotonated BH₃-protected resin-bound potassium phosphides K₂a–d as yellow-orange resins after one hour (Scheme 2, step 1). Subsequent reaction of K₂a–d with a slight excess of 1a–h (1:1 equiv) gave access to the air-stable immobilized borane-protected PNP ligands 3a–n (Scheme 2, step 2). The incorporation of the PN fragment was monitored by gel-phase ³¹P NMR showing both the quantitative consumption of the potassium phosphide and the appearance of a second resonance in a 1:1 ratio (see Figure 3 for representative synthesis of 3f). Although the signal of the first phosphine–borane in close proximity to the support appears very broad, the remote phosphorous moiety shows a significantly sharper signal due to enhanced solution-like behavior.

After removal of the borane groups by treatment with a large excess of diethylamine at 50 °C, the resin-bound PNP-pincer ligands L₁–L₁₄ were obtained. In the presence of more bulky -PPh₃ and -PAd (Ad = adamantyl) groups, several replacements with fresh diethylamine as well as longer reaction times were required. Quantitative deprotection of both phosphine moieties was readily monitored by ³¹P NMR, indicated by a significant highfield shift of all corresponding phosphorus signals. The representative synthesis of L₄ monitored by gel-phase ³¹P NMR is depicted in Figure 3.

All resin-bound PNP ligands were synthesized in high yields and purity. Only simple filtration and washing steps were required for purification demonstrating the power of the solid-phase synthesis approach. Finally, the actual phosphorus loading was determined by elemental analysis.

Through systematic variation of the phosphine substituents R¹, R², and R³ as well as by employing three different types of polymeric supports, a combinatorial library of 14 different supported PNP pincer ligands was efficiently accessed through a solid-phase synthetic approach (Figure 4). In contrast to structurally similar homogeneous analogues, ligands L₁–L₁₄ represent nonsymmetrical ligands which have been rarely investigated in solution-phase. However, the combination of two phosphorus moieties exhibiting different electronic and steric properties offers great potential for efficient catalyst tuning. Among all library members, only the nonsymmetrical solution-phase analogues of L₄ and L₅, as well as the nearly symmetrical ligand L₁₄ have been reported previously. The ³¹P NMR spectra for both reported examples are well in line with those obtained for their heterogenized equivalents.

In analogy to the synthesis in monophasic systems, the resin-bound ligands were reacted with the ruthenium precursor [RuHCl(PPh₃)₃CO] at 60 °C in THF to afford the corresponding resin-bound Ru-PNP complexes C₁–C₁₄ (Scheme 3). The progress of the reaction was monitored by ³¹P NMR indicating full displacement of PPh₃ together with the quantitative disappearance of the free PNP ligand signals.

The gel-phase ³¹P NMR spectra of complexes C₁, C₅, C₇, and C₉–C₁₂ reveal two new broad resonances occurring in a 1:1 ratio, which correspond to both phosphine moieties coordinated to the ruthenium center. Due to the lack of solvent-dependent swelling properties of C₇, and C₁₀ immobilized on the
higher cross-linked MF 4% resin, the signals appear significantly broadened compared with complexes immobilized on supports with 1% cross-linking. The representative synthesis of C6 monitored by 31P NMR is depicted in Figure 5.

The signal of the -P(tBu)2 group is shifted from δ = 35.5 in L6 to δ = 91.2 ppm, whereas the resonance of the resin-bound -PPh moiety arises at δ = 56.5 in C6 in contrast to δ = −13.9 ppm in the free ligand. The phosphine resonances in C1–C3 and C6 overlap leading to a single broad peak whereas the gel-phase 31P NMR spectra for C6 and C14 reveal three broad signals. The latter can be attributed to the presence of a racemic -P(PhtBu) group in both complexes leading to a difference of up to Δ11–15 ppm between the corresponding signals of the stereoisomers. Due to significant peak broadening in the gel-phase NMR of C14, the immobilized complex was analyzed using solid-state NMR techniques. The 31P MAS NMR spectrum shows two signals appearing in a ratio of 1:1 at δ = 78.9 and δ = 65.1 ppm corresponding to the two chemically different phosphorus donor atoms (Figure 6a). The chemical shifts of C14 are in line with those obtained for the homogeneous Ru-PNP counterpart XVII reported by Arenas et al. (Figure 7).[28]

Unfortunately, due to significant peak broadening commonly observed for polymer-bound complexes, coupling constants could not be determined in solid-state and gel-phase NMR.[13, 27a,29] Among the broad signals belonging to the aromatic and aliphatic protons of the polymeric backbone, the hydride ligand of C14 was observed at a distinct shift of −13.85 ppm in the 1H MAS NMR (Figure 6b).

In the 13C CP/MAS spectrum the CO peak appears at δ = 211.0 ppm. Characteristic pyridine signals at δ = 162.1, 145.5, and 120.1 ppm are overlapped by the aromatic signals belonging to the ligand phenyl group as well as to the support (Figure 6c). Resonances of tBu are observed at δ = 35.0, 31.9, and 27.5 ppm. The signals corresponding to the methylene side-arms can be expected at 40.5 ppm but are overlapping with the peaks of the support.

To gain additional evidence of the molecular structure of supported complex C6, the homogeneous Ru-P3NPtBu analogue 5 was prepared. Two different phosphorus donor moieties bearing both Ph and tBu substituents are present in the nonsymmetrical PNP pincer ligand. These were introduced by reacting 1a with 1.0 equivalent of borane protected lithium di-

Figure 4. Complete library of supported PNP pincer ligands L1–L14.

Scheme 3. Solid-phase synthesis of resin-bound Ru-PNP complexes C1–C14.

Figure 5. Solid-phase synthesis of supported Ru-PNP complex C6 monitored by 31P NMR.
tert-butylphosphide leading to the nonsymmetrical borane-protected PNP ligand 4 in 91% yield (Scheme 4, step 1).

Removal of the borane groups by treatment with an excess of diethylamine followed by complexation using [RuHCl(PPh3)3CO] in THF at 60°C led to 5 in 83% yield (Scheme 4, steps 2 and 3).

Single crystals suitable for X-ray crystallography were obtained by slow diffusion of n-pentane into a solution of 5 in CH2Cl2. As shown in Figure 8, the complex exhibits a distorted octahedral geometry around the RuII center with trans-coordination of the CO ligand to the nitrogen atom of pyridine and the hydride trans to the chloride. Hence, a meridional coordination geometry of the PNP ligand around the metal center is obtained as reported for symmetrical pyridine-based [RuHCl(PNP)CO] complexes.10

The hydride ligand exhibits a doublet of doublets in the 1H NMR spectrum at δ = -14.51 ppm (JHP = 17.1 and 20.5 Hz) as found in similar Ru-complexes.28-31 The diastereotopic protons of the -PPh2 methylene arm show signals at δ = 4.89 ppm (dd, JPH = 9.5, JHH = 16.0 Hz) and at δ = 4.12 ppm (dd, JHH = 2.6, JHH = 12.1, JHH = 16.0 Hz). A multiplet at δ = 3.73–3.66 ppm and a doublet of doublets at δ = 3.37 ppm (JHH = 8.3, JHH = 16.6 Hz) were observed for both methylene protons belonging to the -PtBu2 methylene linker. In the 31P NMR, the CO ligand appears as a triplet (JPC = 12.2 Hz) at δ = 208.9 ppm (see the Supporting Information for details). Finally, the 31P(1H) NMR spectrum of 5...
shows two doublets corresponding to the -PtBu$_2$ (δ = 90.4 ppm, $J_D = 266.6$ Hz) and the -PPh$_2$ entity (δ = 53.6 ppm, $J_D = 266.6$ Hz) bound to the central Ru atom (Figure 9, red spectrum). These results compare well to the $^{31}$P NMR resonances at δ = 91.2 and 56.5 ppm obtained for the correlating supported Ru-complex C$_9$ differing only in the methylene linker to the MF support (Figure 9, black spectrum). The CO stretching band in the FT-IR spectrum of 5 was observed at 1887 cm$^{-1}$.

Subsequently, the supported combinatorial Ru-PNP library (C$_1$–C$_{14}$) was screened in the hydrogenation of methyl benzoate (S$_2$). The catalytic reactions were performed under optimized conditions over 16 hours in THF at 80°C and 50 bar H$_2$ pressure. Further reaction conditions are listed in Table S1 (see the Supporting Information). For supported catalysts C$_9$, bearing phenyl groups on both phosphine moieties of the PNP ligand, 84% conversion and 92% selectivity towards the desired benzyl alcohol (BzOH) were obtained (Table 1, entry 1). By changing to more electron-donating 4-MeOPh groups bound to the remote phosphine in C$_{16}$ an increase in catalyst activity (97%) and selectivity (99%) was observed compared with C$_9$ (Table 1, entry 2). Electron-withdrawing 4-ClPh groups in C$_5$ led to a reduced activity of 69% conversion and more transesterification to benzyl benzoate (BzBz, Table 1, entry 3). When changing to unsymmetrical ligands carrying aromatic substituents on the resin-bound phosphorus-donor and alkyl substituents on the remote phosphine, moderate activities were obtained for C$_4$ and C$_9$ (Table 1, entries 4 and 5). With increasing steric demand in case of strong electron-donating Bz groups (C$_9$) or even more bulky adamantyl groups (C$_{13}$), excellent conversions were reached with full selectivity towards BzOH (Table 1, entries 6 and 10). Opposed to the high activity and selectivity at room temperature for the reported resin-bound Ru-PNN system (XVI),$^{[25]}$ a reduced temperature of 60°C resulted in lower conversion of 82% in case of C$_8$ (Table 1, entry 7). When applying the equivalent catalysts C$_9$ and C$_{13}$ immobilized on the higher cross-linked resin MF 4%, reduced performances (64–65% conversion, 83–84% selectivity) compared with C$_5$ and C$_9$ immobilized on MF 1% were found (Table 1, entries 8 and 11 vs. 6 and 10). This can be attributed to the lack of solvent dependent gel-like behavior of the higher cross-linked polymer and the consequently reduced accessibility of the catalytically active sites within the support.

Supported catalyst C$_9$ bearing both a Ph and Bz substituent on the remote phosphine led to 89% conversion and 96% selectivity (Table 1, entry 9). Hence, catalytic activity for catalysts with R$_2$=Ph rises with gradual increase of steric bulk and electron-donating properties in the series C$_1$<C$_3$<C$_6$. Replacing R$_1$=Ph by a Cy group on the resin-bound phosphorus donor led to slightly reduced performances for C$_{11}$ and C$_{12}$ compared with the corresponding complexes C$_9$ and C$_8$ (Table 1, entries 12 and 13). Catalysts C$_{13}$ and C$_{14}$ supported on PS-resin with R$_2$=Bz gave even less activity than their phenyl analogues C$_9$ and C$_8$ (Table 1, entries 14 and 15). Surprisingly, when the nonsymmetrical solution-phase complex 5 was applied under the same conditions, only 78% conversion was reached compared with 98% of its heterogenized counterpart C$_9$ (Table 1, entries 6 and 16). This indicates that the support does not exert a detrimental effect on the performance contrary to reports for many known immobilized catalysts.

Subsequently, the substrate scope was determined employing the best-performing supported catalysts C$_8$ and C$_9$ in the
hydrogenation of monoesters S₁–S₈, diesters S₉–S₁₀, and lactones S₁₁–S₁₂ (Figure 10). Although the aromatic ester ethyl benzoate (S₂) was hydrogenated with slightly reduced conversion and selectivity compared with S₄, benzyl benzoate (S₉) proved to be more challenging (69% conversion).

When employing catalyst C₉, even less activity (44%) was observed towards the formation of BzOH. Linear alkyl esters gave up to 84% conversion and 86% selectivity to the primary alcohol in case of methyl hexanoate (S₄) whereas ethyl hexanoate (S₅) and hexyl hexanoate (S₆) also proved to be more challenging substrates. Again, better performances were achieved when using C₆ instead of C₉. Branched alkyl esters, such as methyl isovalerate (S₇) and methyl cyclohexanoate (S₈), were converted more readily than their linear analogues with 84% conversion and 86% selectivity for S₈. Reported for the supported Ru-PNN catalyst XVI, no conversion was observed for diethyl succinate (S₉).

This could be attributed to a chelating coordination of the short-chain diester to the catalyst. When extending the carbon chain length by using dodecanedioate (S₁₀), 70% of the diester was converted after 24 h yielding the monohydrogenated product as the main product whereas only 11% of the diol was formed. At 2.0 mol% catalyst loading and 100 °C, excellent conversion of S₁₀ was obtained with 74% selectivity towards the desired 1,12-dodecanediol. Finally, g-butyrolactone (S₁₁) and biomass-derived γ-valerolactone (S₁₂) were selectively converted into the corresponding diols underlining the versatility of the heterogenized Ru-PNP system.

Finally, the recovery and recyclability of the supported Ru-PNP catalyst C₆ was investigated in the hydrogenation of S₁ (Table 2). It was decided to shorten the reaction time from 16 to 2 h to assess any effect on the catalyst performance as a consequence of catalyst deactivation. After each cycle, the supernatant solution was filtered off followed by addition of

### Table 1. Ru-catalyzed hydrogenation of S₁ using supported catalysts C₁–C₁₄

| Entry | Cat. | R₁ | R₂ | R₃ | Conversion [%][b] | Selectivity [%][c] |
|-------|-----|----|----|----|------------------|-------------------|
| 1     | C₁  | Ph | Ph | Ph | 84             | 92                |
| 2     | C₂  | Ph | 4-MeOPh | 4-MeOPh | 97             | 99                |
| 3     | C₃  | Ph | 4-ClPh | 4-ClPh | 69             | 84                |
| 4     | C₄  | Ph | Cy | Cy | 61             | 83                |
| 5     | C₅  | Ph | iBu | iBu | 58             | 86                |
| 6     | C₆  | Ph | tBu | tBu | 98             | 99                |
| 7     | C₇  | Ph | tBu | tBu | 94             | 98                |
| 8     | C₈  | Ph | Ph | Ph | 94             | 98                |
| 9     | C₉  | Ph | Ad | Ad | >99             | >99               |
| 10    | C₁₀ | Ph | Ad | Ad | 65             | 83                |
| 11    | C₁₁ | Cy | Cy | Ph | 72             | 88                |
| 12    | C₁₂ | Cy | Ph | tBu | 80             | 90                |
| 13    | C₁₃ | iBu | iBu | tBu | 70             | 86                |
| 14    | C₁₄ | Ph | tBu | tBu | 78             | 94                |
| 15    | C₁₅ | Ph | Ph | tBu | 78             | 94                |
| 16    | C₁₆ | Ph | Ph | tBu | 78             | 94                |

[a] General conditions: substrate (0.5 mmol), [Ru] (1.0 mol%), KOtBu (10 mol%), THF (1 mL), 80 °C, H₂ (50 bar), 16 h. [b] Conversion of S₁ determined by GC using dodecane as internal standard. [c] Selectivity towards BzOH. [d] 60 °C.
Table 2. Batch recycling using C\textsubscript{1} in the hydrogenation of S\textsubscript{78}.

| Entry | Conversion [%] | Selectivity [%] |
|-------|---------------|-----------------|
| 1     | 44            | 77              |
| 2     | 40            | 75              |
| 3     | 40            | 74              |
| 4     | 36            | 70              |
| 5     | 33            | 68              |

[a] Conditions: substrate (0.5 mmol), C\textsubscript{1} (1.0 mol%), KO\textsubscript{t}Bu (10 mol%), THF (1 mL), 100 °C, H\textsubscript{2} (50 bar), 2 h. [b] Conversion of S\textsubscript{78} determined by GC using dodecane as internal standard. [c] Selectivity towards BzOH.

Conclusions

We developed the first facile access to a combinatorial library of nonsymmetrical resin-bound PNP pincer-type ligands by employing a solid-phase synthesis approach. Systematic variation of phosphine substituents combined with the use of three different types of polymeric supports led to a library with 14 members (L\textsubscript{1}–L\textsubscript{14}). The supported ligands were obtained in high purity only requiring minimal purification steps opposite to typically arduous synthetic protocols for solution-phase analogues. The immobilized nonsymmetrical PNP ligands offer higher potential for efficient fine-tuning of stereo-electronic ligand properties compared with C\textsubscript{60} symmetrical ligands. The corresponding resin-bound Ru-PNP complexes C\textsubscript{1}–C\textsubscript{14} were successfully screened in the hydrogenation of methyl benzoate (S\textsubscript{78}) under mild conditions. Minor changes within the structure of the phosphine substituents had a substantial impact on catalyst performances underlining the necessity of catalyst screening. A broad range of monoesters and long-chain diester S\textsubscript{78} were hydrogenated to the desired alcohols under mild conditions. Lactones, such as bioderived \textgamma-valerolactone (S\textsubscript{12}), could be readily converted with high selectivities towards the corresponding diols. Preliminary recycling experiments indicated facile recovery and reusability of the supported catalyst.

Experimental Section

General procedure for the synthesis of 1a–g

To a solution of secondary phosphine-borane adduct (1.0 equiv) in dry THF at −78 °C, nBuLi (2.5 M in hexanes, 1.0 equiv) or sec-BuLi (1.4 M in cyclohexane, 1.0 equiv) in case of (adamantyl)P=HB\textsubscript{11} was added dropwise. The solution was stirred for 30 min at −78 °C and subsequently warmed to room temperature and was left for an additional amount of time until full conversion was achieved according to \textsuperscript{31}P NMR. 2,6-Bis(chloromethyl)pyridine (1.0 equiv) was dissolved in dry THF and cooled to −78 °C. Next, the freshly prepared lithium boranyl phosphane solution (0.28 M, 1.0 equiv) in THF was added slowly. The mixture was warmed up to room temperature overnight leading to a pale-yellow solution. The solvent was removed under vacuum and the yellow residue was dissolved in CH\textsubscript{2}Cl\textsubscript{2}. The organic phase was washed with water and brine and subsequently dried over MgSO\textsubscript{4}. After filtration, the solvent was removed under reduced pressure. The residue was purified through flash chromatography (9:1 hexanes/ethyl acetate) or as stated otherwise yielding a white solid.

General procedure for the synthesis of resin-bound PNP-pincer ligands L\textsubscript{1}–L\textsubscript{14}

Step 1: A resin-bound phosphine-borane (2a, 1.40 g, 1.57 mmol, 1.0 equiv), (2b, 0.22 g, 0.24 mmol, 1.0 equiv), (2c, 0.25 g, 0.28 mmol, 1.0 equiv), or (2d, 0.12 g, 0.22 mmol, 1.0 equiv) was swollen in THF (20 mL). After addition of KH\textsubscript{2}DS (20% in THF, 10 equiv) under gentle stirring to avoid mechanical abrasion of the resin, the orange resin was allowed to cool for 2 hours at room temperature. The supernatant was removed and the resin was washed three times with THF (15 mL) followed by three times with Et\textsubscript{2}O (15 mL). Without further purification, the BH\textsubscript{11}-protected resin-bound potassium phosphides were used in the next step.

Step 2: A previously synthesized BH\textsubscript{11}-protected resin-bound potassium phosphide (K\textsubscript{2}a, 1.57 mmol, 1.0 equiv), (K\textsubscript{2}b, 0.24 mmol, 1.0 equiv), (K\textsubscript{2}c, 0.28 mmol, 1.0 equiv), or (K\textsubscript{2}d, 0.22 mmol, 1.0 equiv) was swollen in THF (10 mL) and cooled to −78 °C. A 2-(chloromethyl)-6-(phenylimethyl)pyridine-borane (1a–h, 1.1 equiv) was azeotropically dried with toluene (3 × 5 mL), dissolved in THF (10 mL) and added to the resin at −78 °C under gentle stirring to avoid mechanical abrasion. The mixture was left with occasional stirring and allowed to warm up to room temperature overnight. The reaction was monitored using gel-phase \textsuperscript{31}P NMR and was allowed to react until full conversion was observed. Next, the supernatant was removed and the resin was washed three times with THF (10 mL) followed by three times with Et\textsubscript{2}O (10 mL) and dried in vacuo yielding a pale yellow resin-bound PNP borane adduct (3a–n).

Step 3: A resin-bound PNP borane adduct 3a–n synthesized in the last step was swollen in 10 mL of diethyl amine and heated to 50 °C overnight with occasional stirring to avoid mechanical abrasion of the resin. The reaction was monitored using gel-phase \textsuperscript{31}P NMR and was allowed to react until full conversion was observed. Next, the mixture was cooled to room temperature and the supernatant was removed. The resin was washed with three portions of THF (10 mL) followed by three portions of Et\textsubscript{2}O (10 mL) and dried in vacuo yielding a pale yellow resin-bound PNP pincer ligand (L\textsubscript{1}–L\textsubscript{14}).
General procedure for the synthesis of resin-bound complexes C₁₋C₁₄

A previously synthesized resin-bound PNP pincer ligand (L₁−L₄₉ ≈ 80−170 mg, 1.0 equiv) and [Ru(HCl(PPh₃)₃)CO] (1.1 equiv) were weighed into a Schlenk tube. The mixture was suspended in THF (10 mL) and heated to 60 °C under gentle stirring. The reaction mixture was left at 60 °C with occasional stirring to avoid mechanical abrasion of the resin and the progress of the reaction was monitored by gel-phase ³¹P NMR. Once full complexation of the resin-bound PNP ligand was observed, the mixture was cooled to room temperature and the supernatant was removed. The resin-bound complex was washed with three portions of THF (10 mL), three portions of CH₂Cl₂ (10 mL) followed by three portions of Et₂O (10 mL). After drying in vacuo, a yellow to brown resin-bound Ru-PNP complex (C₁₋C₁₄) was obtained.

General procedure for Ru-catalyzed ester hydrogenation

The hydrogenation experiments were performed in a stainless steel autoclave charged with an insert suitable for up to 12 reaction vessels (2 mL) including Teflon mini stir bars. Inside a glove box, a reaction vessel was charged with a resin-bound Ru-PNP complex (C₁₋C₁₄ (≈ 7 mg, 5.0 μmol, 1.0 mol%). To the reaction vessel 0.5 mL of a stock solution of KO(BU₄)₃ (10 mol%) in THF was added and the mixture was stirred for 5 minutes. Next, 0.5 mL of the substrates S₁−S₅ (0.5 mmol) and the internal standard dodecane (50 mol %) dissolved in THF were added. Subsequently, the autoclave was purged three times with 10 bar of argon gas and the insert loaded with reaction vessels was transferred into the autoclave. Next, the autoclave was purged three times with 10 bar of argon gas and the insert loaded with reaction vessels was transferred into the autoclave. The reaction mixtures were gently stirred at 450 rpm for 16–24 hours. The autoclave was cooled to room temperature and the supernatant was removed. The resin-bound PNP ligand was observed, the mixture was cooled to 60 °C (10 mL) and heated to 60 °C (10 mL) followed by three portions of Et₂O (10 mL). The authors declare no conflict of interest.

The authors declare no conflict of interest.

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