SYNTHESIS OF BIFUNCTIONAL MANGANESE COMPLEXES AND THEIR APPLICATION IN TRANSFER HYDROGENATION OF NITRILES

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Abstract

A series of bifunctional Mn(0), Mn(I), and Mn(II) complexes bearing polydentate ligands with secondary amino functionality were prepared, characterized, and tested as pre-catalysts in transfer hydrogenation of nitriles to amines using ammonia borane as a reducing agent in the presence of 5 mol% of Mn(I) or Mn(II) pre-catalysts, aromatic and aliphatic substrates were converted to either primary or secondary amines 24 h at 80 ºC. Primary amine products were isolated as their hydrochloride salts, obtained by the treatment of the reaction mixtures with HCl. Transfer hydrogenation reactions were found to be highly sensitive to the choice of solvent (benzene *vs.* isopropanol) and the nature of the catalyst used. The superior catalytic activity in transfer hydrogenation of nitriles to primary amines was demonstrated for Mn(I) complexes bearing tridentate $PN^{H}N$ of bidentate PN^{H} ligands. Moreover, high turnovers of nitriles to primary amines have been also demonstrated for the readily accessible phosphine-free $NN^{H}O$ Mn(II) complex. Catalytic reduction reactions were proposed to proceed *via* a metal-ligand cooperative mechanism and do not require the use of pressurized hydrogen gas and base additives for catalyst activation.

Acknowledgements

Foremost, I would like to express my sincere gratitude to my research supervisor Dr. Andrey Y. Khalimon for his support, patience, and faith in me for my MSc study. The guidance and advice provided by Dr. Khalimon have been helpful in my thesis research. The completion of this MSc thesis could not have been accomplished without this support.

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Finally, my deepest appreciation goes to my family, especially my mother and sister for their belief in me has kept my spirits and motivation high during this process.

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List of Abbreviations & Symbols

TH	Transfer Hydrogenation
TM	Transition metal
ppm	Parts per million
DCM	Dichloromethane
DCE	Dichloroethane
THF	Tetrahydrofuran
NMR	Nuclear Magnetic Resonance
DCM-d_2	Deuterated dichloromethane
DPPB	1,4-Bis(diphenylphosphino)butane
HFIP	Hexafluoroisopropanol
BA	Benzylamine
BI	N-benzyl-1-phenylmethanimine
NR	No reaction
DPA	Dipycolylamine

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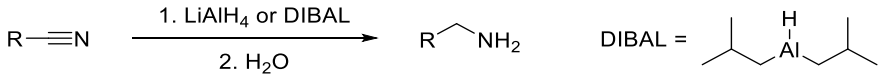
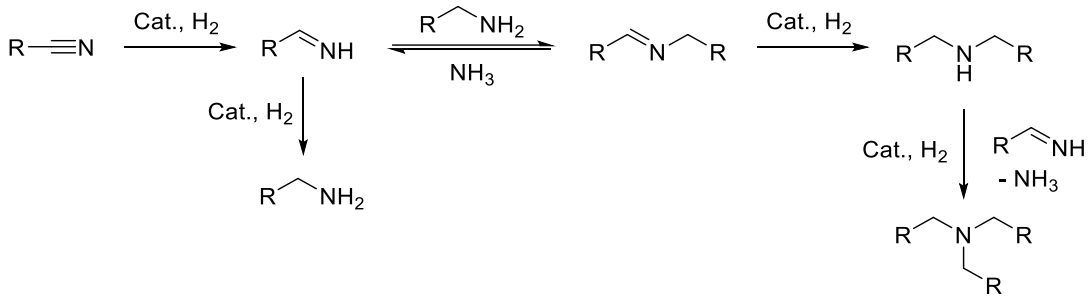
1 Introduction

The reduction of unsaturated nitrogen containing compounds to amines is one of the important transformations in synthetic chemistry [1-5]. Because of the significance of amines as organic building blocks in the synthesis of natural products, pharmaceuticals and agrochemicals, precursors in the preparation of azo dyes and other commodity and specialty products, the development of efficient and selective methods for preparation of amines represents an important task [1-7]. In this regard, due to their easy accessibility, nitriles are considered as attractive precursors to a large variety of synthetically important amines. Although, the reduction of nitriles can be achieved *via* stochiometric reactions with metal hydrides (e.g., $LiAlH_4$ or DIBAL (diisobutylaluminum hydride) etc.; Scheme 1), these reagents typically result in non-selective transformations due to low functional group tolerance and generate large amount of salt wastes [7-9]. On the other hand, the most atom-economical approach, catalytic hydrogenation of nitriles with molecular hydrogen (Scheme 2) typically suffers from harsh reaction conditions (high pressures and temperatures) and the necessity of expensive high-pressure equipment [10]. Moreover, harsh reaction conditions for hydrogenation catalysis often lead to difficult–to–separate mixtures of primary, secondary and tertiary amines along with secondary imine products (Scheme 2) [9-10].

Scheme 1. Stoichiometric reduction of nitriles to amines.



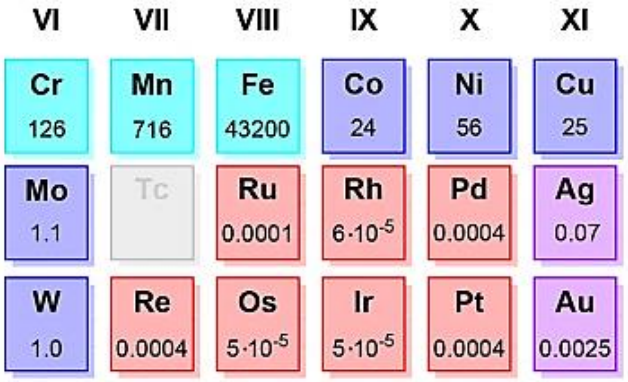
Scheme 2. Catalytic hydrogenation of nitriles.



An alternative approach that avoids the use of pressurized hydrogen gas is based on transfer hydrogenation (TH) catalysis using readily available and easy to handle liquid and/or solid hydrogen donors, such as alcohols, formic acid, ammonia borane and others [8-10]. This allows to perform the reduction under comparatively mild reaction conditions, which ultimately leads to a better control of the selectivity of transformations [11].

Conventional TH catalysts are based on precious metals such as ruthenium, rhodium, iridium [11]. Due to low natural abundance of these metals (Figure 1) and their recognized toxicity, the development of efficient transfer hydrogenation catalysts based on more economical and less toxic 3d transition metals (Mn, Fe, Co, Ni; so-called base metals) have become an important research agenda in this field [11]. Whereas such systems have been successfully applied in transfer hydrogenation of aldehydes, ketones, esters and even alkenes [12-15], selective and efficient base metal catalysts for TH of nitriles are developed to a lesser extent.

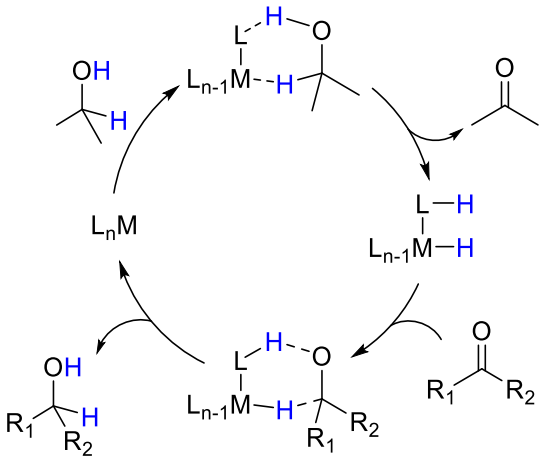
Figure 1. Natural abundance (in ppm) of group 6-11 transition metals.



Our research group has a long-standing interest in the design of homogeneous base metal catalysts for selective reduction of unsaturated organic molecules, including *N*-containing compounds. The previous group results include efficient cobalt- and nickel-based systems for hydrosilylation and hydroboration of nitriles, nitro compounds, isocyanates, carboxamides, as well as transfer hydrogenation of aldehydes and ketones [16-21]. The goal of the current work is the development of manganese pre-catalysts for transfer hydrogenation of nitriles. Manganese is second most abundant base metal after iron, and high catalytic activity of manganese complexes has been already demonstrated in the reduction of carbonyl compounds [22-23]. However, only scarce examples of efficient Mn systems for transfer hydrogenation of unsaturated *N*-containing organic molecules, have been reported [24-25]. Therefore, this work is focused on the preparation and evaluation of catalytic activities in TH of nitriles of a series of manganese complexes with polydentate bifunctional ligands bearing a secondary amine functionality. Such ligands have already proved effective in catalytic TH of carbonyl compounds with alcohols as hydrogen donors, allowing for metal-ligand cooperative hydrogen transfer processes (Scheme 3) [16]. Therefore, the first part of the study is aimed at the development and characterization of Mn(0), Mn(I) and Mn(II) complexes. In the second part, the catalytic activity of the prepared complexes in TH of nitriles with ammonia borane and the scope of this transformation are discussed. The literature review part

describes the advances in homogeneous transition metal-catalyzed transfer hydrogenation of nitriles to amines using both precious and base metal catalysts.

Scheme 3. Mechanism for the TH of carbonyl compounds with 2-propanol as the hydrogen source: metal-ligand cooperative route.



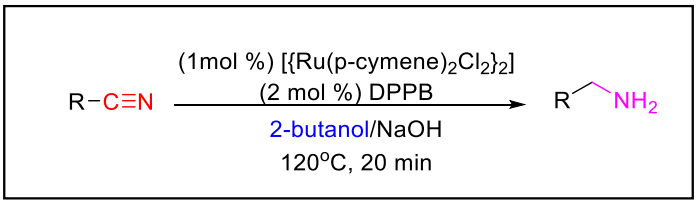
2 Literature Review

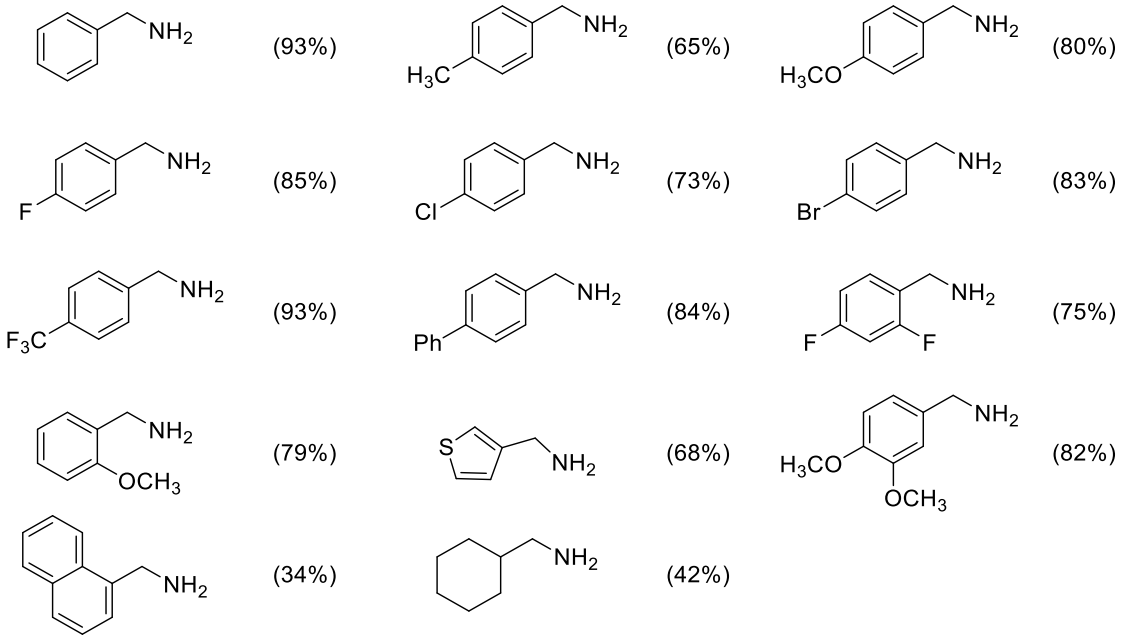
This part of the thesis describes the advances in homogeneous catalytic transfer hydrogenation of nitriles to amines using catalysts based on both precious metals and abundant 3d metals. Special attention here is paid to the strategies for catalyst design and the mechanisms of catalytic transformations. The review starts with the discussion of conventional Ru-based catalytic systems, which is followed by the overview of base metal catalysts.

2.1 Precious metal-catalyzed transfer hydrogenation of nitriles

Probably the first example of Ru-catalyzed TH of nitriles to primary amines was disclosed by Beller *et al.* in 2013 [26]. A series of ruthenium complexes with various ligands were studied as pre-catalysts in TH reactions using alcohols as hydrogen donors. After the screening of different pre-catalyst systems and alcohols, the highest catalytic activity in TH of nitriles was observed for [{Ru(p-cymene)$_2$Cl$_2$}$_2$]/DPPB (DPPB = 1,4-bis(diphenylphosphino)butane) with 2-butanol. The reactions were activated by the addition of NaOH and required heating to 120 °C, albeit, overall, moderate to good yields of amine products were observed (Scheme 4).

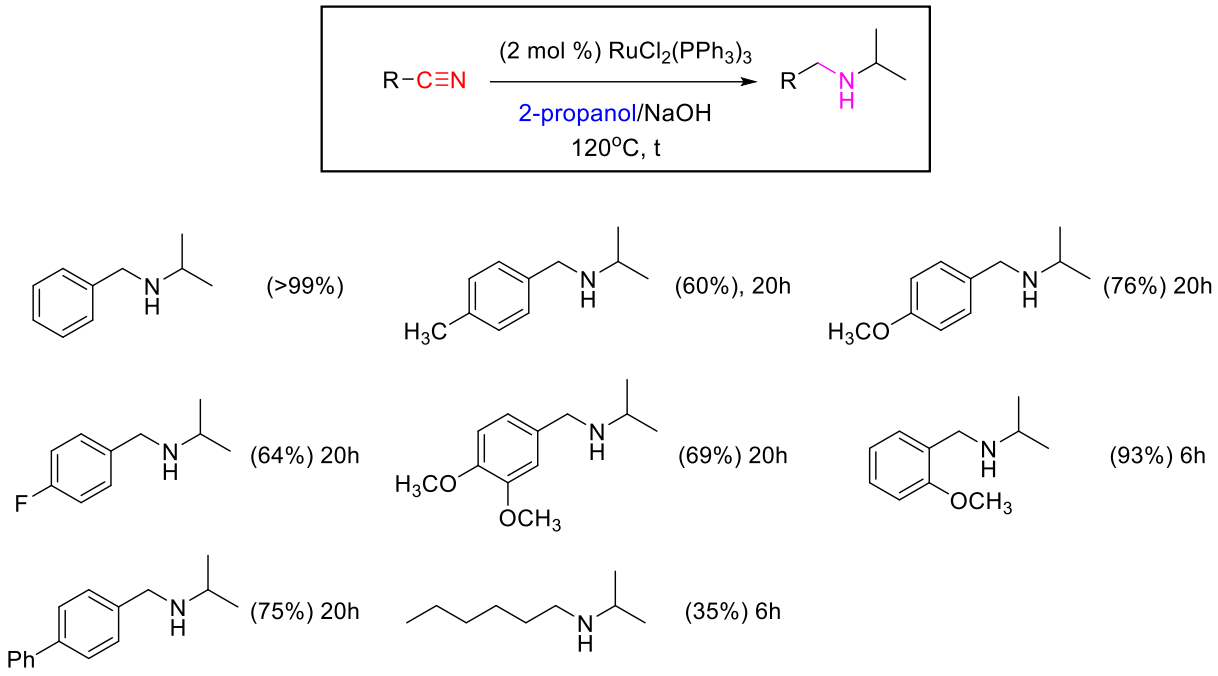
Scheme 4. [{Ru(p-cymene)$_2$Cl$_2$}]/DPPB catalyzed TH of nitriles in 2-butanol.





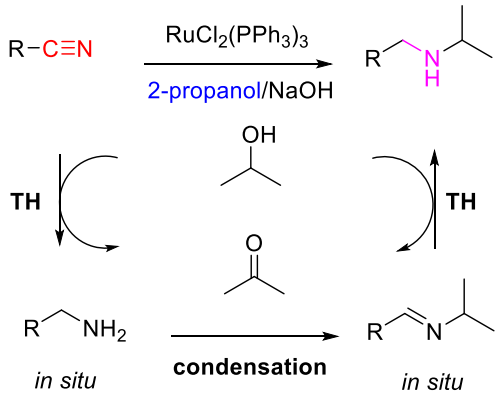
Notably, apart from the desired primary amine products, formation of secondary amine by-products was also detected. Based on these observations, the Ru(II) system was tuned for a cascade TH and monoalkylation of nitriles using 2-propanol as both hydrogen donor and the alkylating reagent [27]. Similarly to the previous study, the reactions were performed at 120 °C using NaOH as an activator, and $RuCl_2(PPh_3)_3$ turned out to be the most active pre-catalyst resulting in efficient one-pot conversion of aromatic nitriles to the corresponding (*N*-isopropyl)benzylamines with moderate to good yields (64->99%; Scheme 5). The reactions worked well for both electron-rich and electron-poor substrates as well as for sterically demanding 2-methoxybenzonitriles; however, rather low yields of amine products were observed for aliphatic substrates (for example, 35% yield was detected for *N*-isopropyl-*n*-hexylamine; Scheme 5).

Scheme 5. $RuCl_2(PPh_3)_3$ catalyzed *N*-monoalkylation of nitriles with 2-propanol.



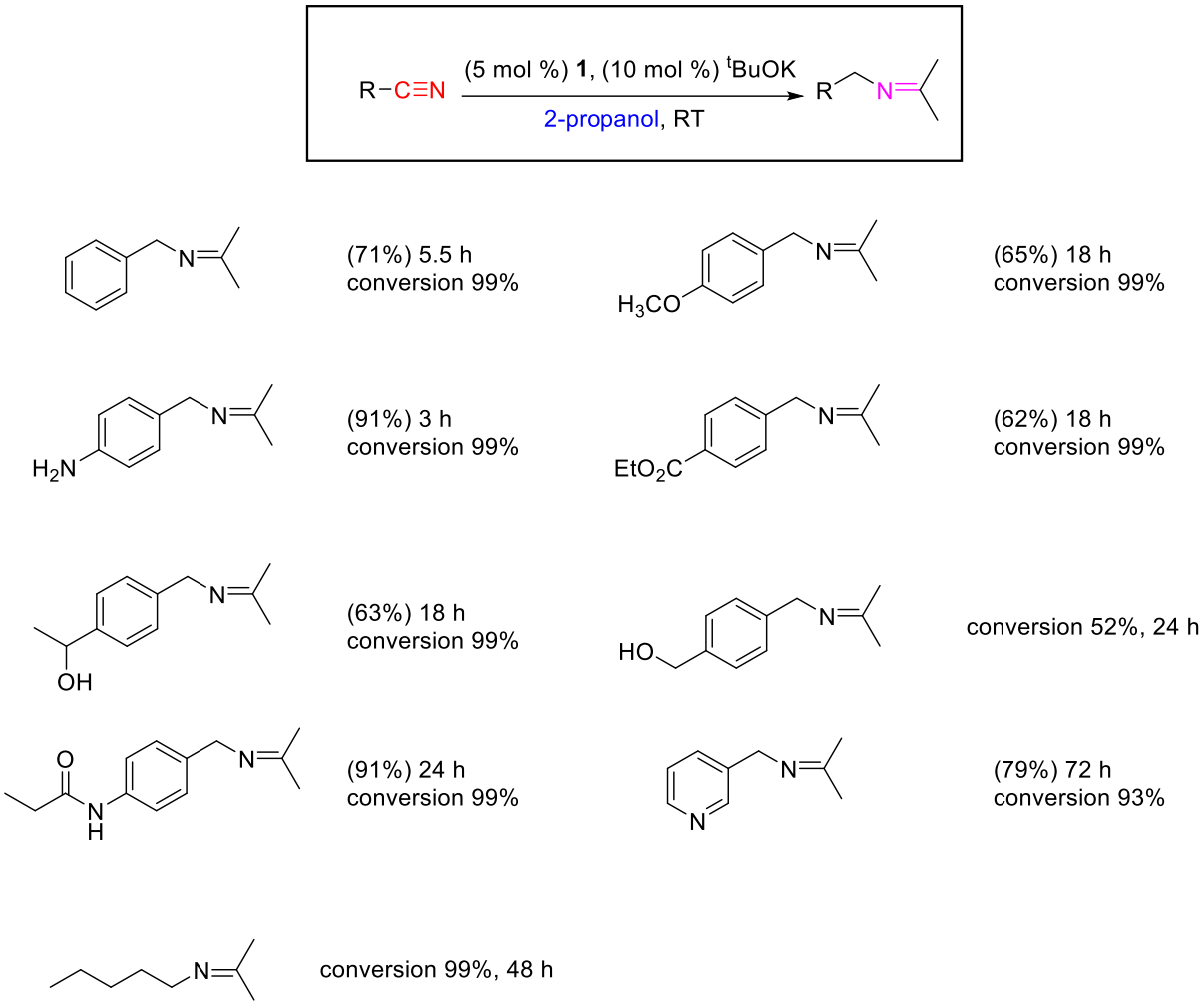
The proposed pathway for Ru-catalyzed *N*-monoalkylation of nitriles is depicted in Scheme 6 and includes $RuCl_2(PPh_3)_3$-catalyzed transfer hydrogenation of nitriles with 2-propanol to primary amines, which then undergo a condensation reaction with acetone (formed by dehydrogenation of 2-propanol) to generate imines. The latter compounds also undergo $RuCl_2(PPh_3)_3$-catalyzed transfer hydrogenation to yield secondary *N*-isopropylamines.

Scheme 6. The proposed reaction pathway for $RuCl_2(PPh_3)_3$-catalyzed TH/monoalkylation of nitriles with 2-propanol.



In 2015, Nikonov *et al.* reported the application of half–sandwich ruthenium complexes for TH of nitriles [28]. This study was inspired by the previously reported high catalytic activity and chemoselectivity of $[Cp(P^iPr_3)Ru(CH_3CN)_2]PF_6$ (**1**) in hydrosilylation of nitriles to the corresponding silylamines [29]. Overall, four ruthenium complexes ($[Cp(P^iPr_3)Ru(CH_3CN)_2]PF_6$ (**1**; Cp = cyclopentadienyl), $[Cp^*(phen)Ru(CH_3CN)]PF_6$ (**2**; Cp* = pentamethylcyclopentadienyl, phen = phenanthroline), $[Cp^*(P^iPr_3)Ru(CH_3CN)]PF_6$ (**3**) and $Cp(P^iPr_3)RuH_3$ (**4**)) were investigated as pre-catalysts/catalysts for TH reactions using 2-propanol as the hydrogen source. In contrast to Beller's reports (*vide supra*), the reactions afforded imines, formed by TH of nitriles to primary amines, followed by their condensation with acetone. No further TH of imine products to secondary amines was observed. Complex **1** proved the most active in these transformations, operating at 5 mol% loading at room temperature (compare to Beller's system that required 120 °C; Schemes 4 and 5 above). The reactions were activated by a strong base KO^tBu (10 mol%) and resulted in excellent conversions of nitriles to the corresponding imine products (up to 99%; Scheme 7). The selected produced imines were hydrolyzed with HCl to afford the corresponding ammonium salts with up to 91% isolated yields. Notably, carboxamides and pyridine functionalities were well-tolerated under the reaction conditions, and **1**-catalyzed TH worked equally well for aromatic and aliphatic nitriles. In contrast, **1**-catalyzed THs of 4-acetylbenzonitrile and 4-cyanobenzaldehyde were found to be non-chemoselective affording mixtures of products of reduction of both carbonyl and nitrile groups. Interestingly, benzonitriles bearing ester functionalities along with the CN reduction underwent transesterification with 2-propanol, whereas no nitrile reduction was observed for alkenyl cyanides.

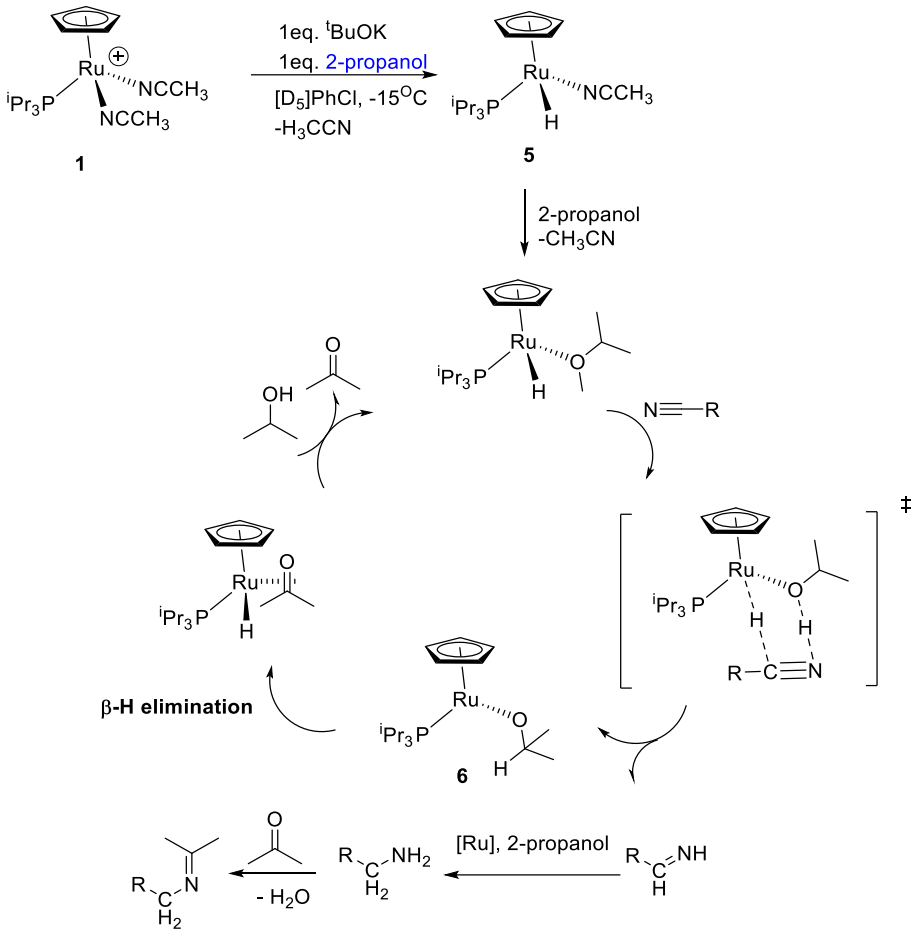
Scheme 7. [Cp(P^iPr_3)Ru(CH_3CN)$_2$]PF_6 (**1**)-catalyzed TH of nitriles to imines with 2-propanol (nitrile conversions and isolated yields of ammonium salts (in parentheses) are shown).



Based on NMR studies, Nikonov *et al.* suggested a hydride mechanism for **1**-catalyzed TH of nitriles with 2-propanol (Scheme 8) [28]. The reaction starts with the activation of **1** by KO^{t}Bu in 2-propanol to generate a neutral Ru(II) hydride species **5**. This is followed by the replacement of the coordinated acetonitrile with 2-propanol and the hydrogen transfer to generate the imine and the Ru(II) isopropoxy intermediate **6**. The subsequent *β*-H elimination generates acetone and recovers the catalyst. Using the same hydrogen transfer mechanism, the produced imine undergoes the second **1**-catalyzed TH to the corresponding primary amine, which undergoes condensation with acetone (produced via dehydrogenation of 2-propanol) to give *N*-isopropylamine product.

Another half-sandwich ruthenium catalyst for TH of nitriles was also reported by Nikonov *et al.* in 2016 [30]. The catalyst contained *N*-heterocyclic carbene ligand (NHC) instead of the phosphine ligand and showed somewhat improved activity at rather low loadings (0.5 mol% *vs*. 5 mol% for **1**). The highest turnover of nitriles to imines was demonstrated for [Cp(IPr)Ru(py)$_2$][PF_6] (**7**; py = pyridine) using 2-propanol as a hydrogen donor and only 1.5 mol%

Scheme 8. The proposed hydride mechanism of **1**-catalyzed TH of nitriles in 2-propanol.

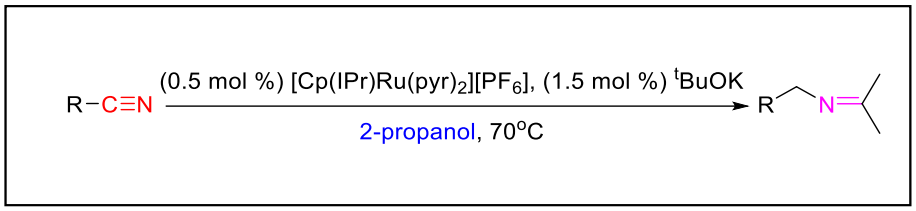


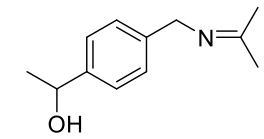
of KO^{t}Bu as activator, albeit the reactions required heating at 70-90 °C. Overall, 14 nitrile substrates were tested showing applicability of the system to both aliphatic and aromatic substrates bearing both electro-donating and electron-withdrawing substituents (Scheme 9). Generally, *para*-substituted benzonitriles resulted in imines with excellent yields of 90-98 %. Similar to **1**-catalyzed reactions (Scheme 7), non-selective TH was observed for 4-acetylbenzonitrile and 4-cyanobenzaldehyde resulting in hydroxy-substituted imine derivatives, although, ester functionalities were well tolerated under TH conditions. Noteworthy, **7**-catalyzed TH of aliphatic nitriles turned out to be more challenging compared to benzonitriles and required the temperature increase from 70 °C to 90 °C and resulted in lower yields of the imine products (Scheme 9).

The proposed mechanism for **7**-catalyzed TH of nitriles is depicted in Scheme 10 and is somewhat similar to the mechanism of **1**-catalyzed transformations. The reactions were suggested to proceed *via* a metal-centered hydride route and start with the activation of complex **7** with KO^{t}Bu in 2-propanol to generate the neutral trihydride species Cp(IPr)Ru(H)$_3$ (**8**). After H_2 dissociation and migratory insertion of the nitrile into the Ru-H bond, an imide intermediate **9** is formed, which is then protonated with 2-propanol to liberate an imine and produce the isopropoxy

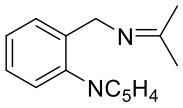
complex **10**. Similarly, to **1**-catalyzed reactions, the catalyst recovery from **10** is suggested to occurs *via* a β-H elimination and the release of a molecule of acetone. The produced primary imine is consequently subjected to the second reduction cycle to form an amine, which is then condensed with acetone to yield an *N*-substituted imine product [28].

Scheme 9. [Cp(iPr)Ru(pyr)$_2$][PF$_6$] catalyzed TH of nitriles to imines.

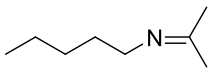




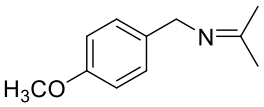
(97%) 45min



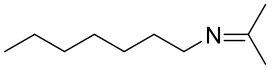
(95%) 165min



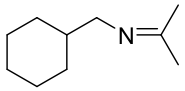
(87%) 48h
90°C



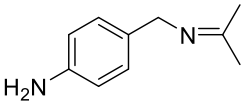
(98%) 50min



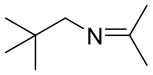
(59%) 48h



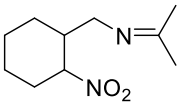
(83%) 120min



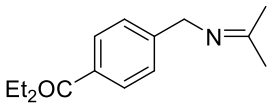
(87%) 90min



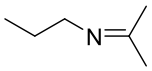
(32%) 48h
90°C



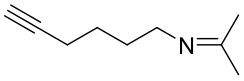
(35%) 48h



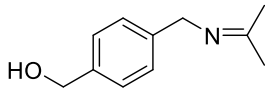
(90%) 195min



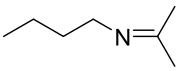
(98%) 48h
90°C



(24%) 48h

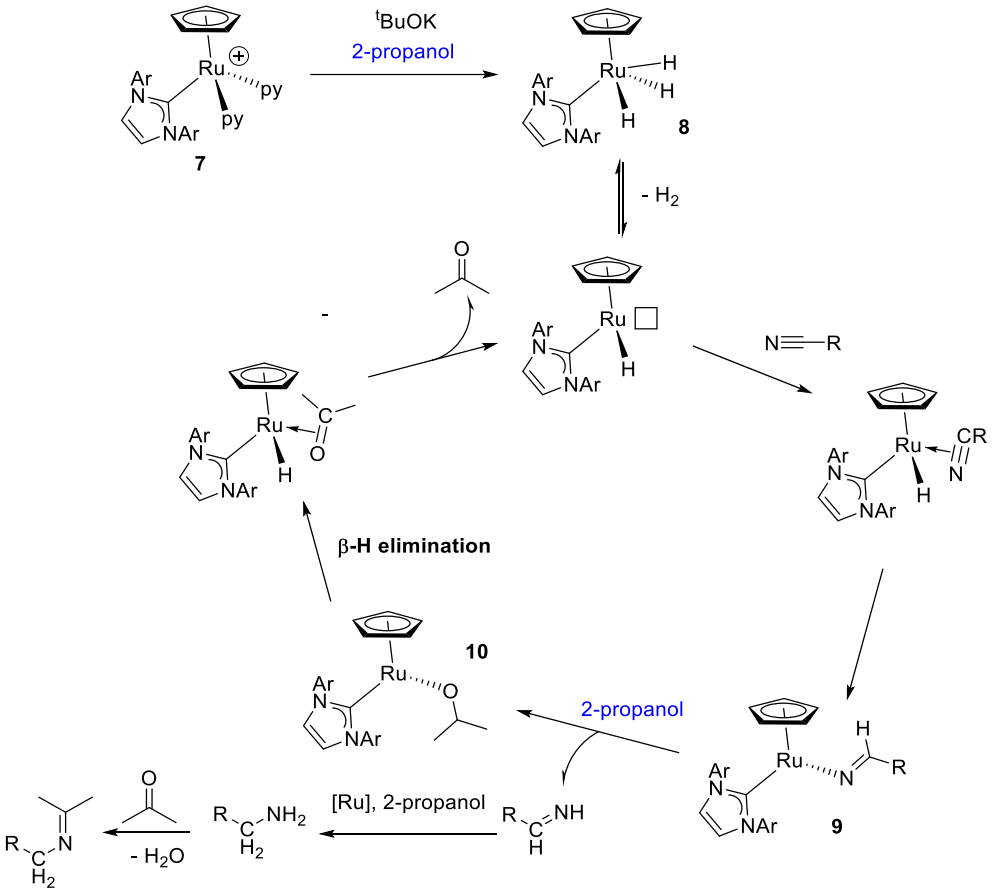


(97%) 120min



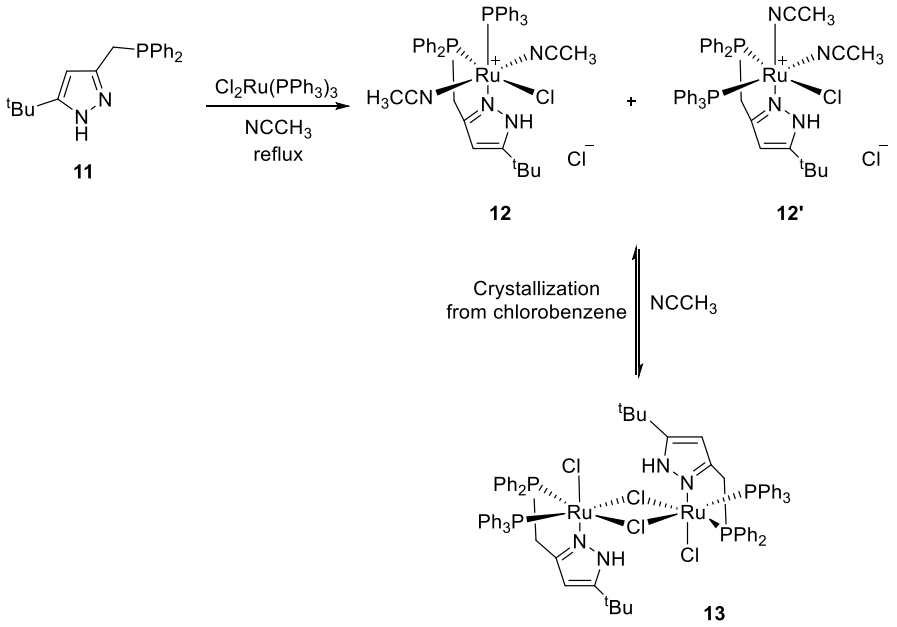
(99%) 48h
90°C

Scheme 10. The proposed hydride mechanism of **7**-catalyzed TH of nitriles in 2-propanol.

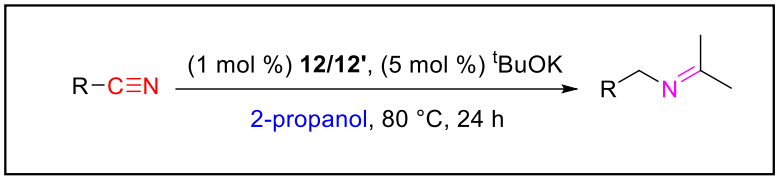


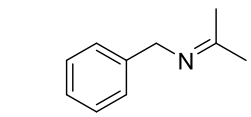
Two years later, another Ru system for TH of nitriles with 2-propanol to imines was reported by Nikonov *et al.* [31]. The design of this catalyst was based on the previously reported Grotjahn's pyrazole/phosphine ligand **11** [32]. Thus, refluxing ligand **11** and $RuCl_2(PPh_3)_3$ in acetonitrile afforded a mixture of two isomeric Ru(II) complexes **12**/**12'**, different by the relative position of coordinated acetonitrile and PPh_3 (Scheme 11). Interesting, that upon crystallization of this mixture of **12** and **12'** from chlorobenzene solution, liberation of coordinated acetonitrile and the formation of a dimeric neutral Ru(II) species **13** was observed (Scheme 11). The mixture of isomers **12** and **12'** was tested in TH of nitriles (9 examples) in 2-propanol (Scheme 12). The reactions required 1 mol% of **12**/**12'**, 5 mol% of KO^{t}Bu as a base activator and heating at 80 °C for 24 h. Notably, aliphatic nitriles and benzonitriles having electron-donating groups (-NH_2, -OMe) were efficiently converted to the corresponding secondary imines (99% conv.), whereas no reactivity was observed for the *para*-nitrobenzonitrile. Steric hindrance in the substrate also seems to play an important role as diminished conversions were detected for 2,6-dimethylbenzonitrile (29%; Scheme 12).

Scheme 11. The synthesis of ruthenium complexes **12** and **12'**.



Scheme 12. 12/12' – catalyzed TH of nitriles to imines in 2-propanol.





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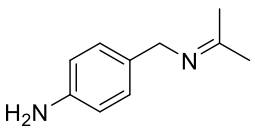

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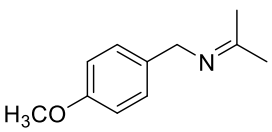

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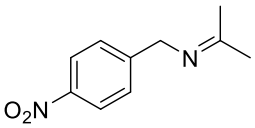

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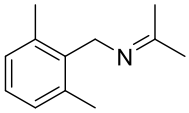

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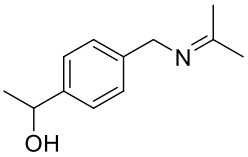

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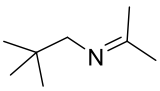

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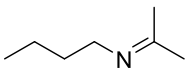

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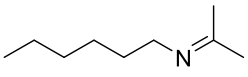


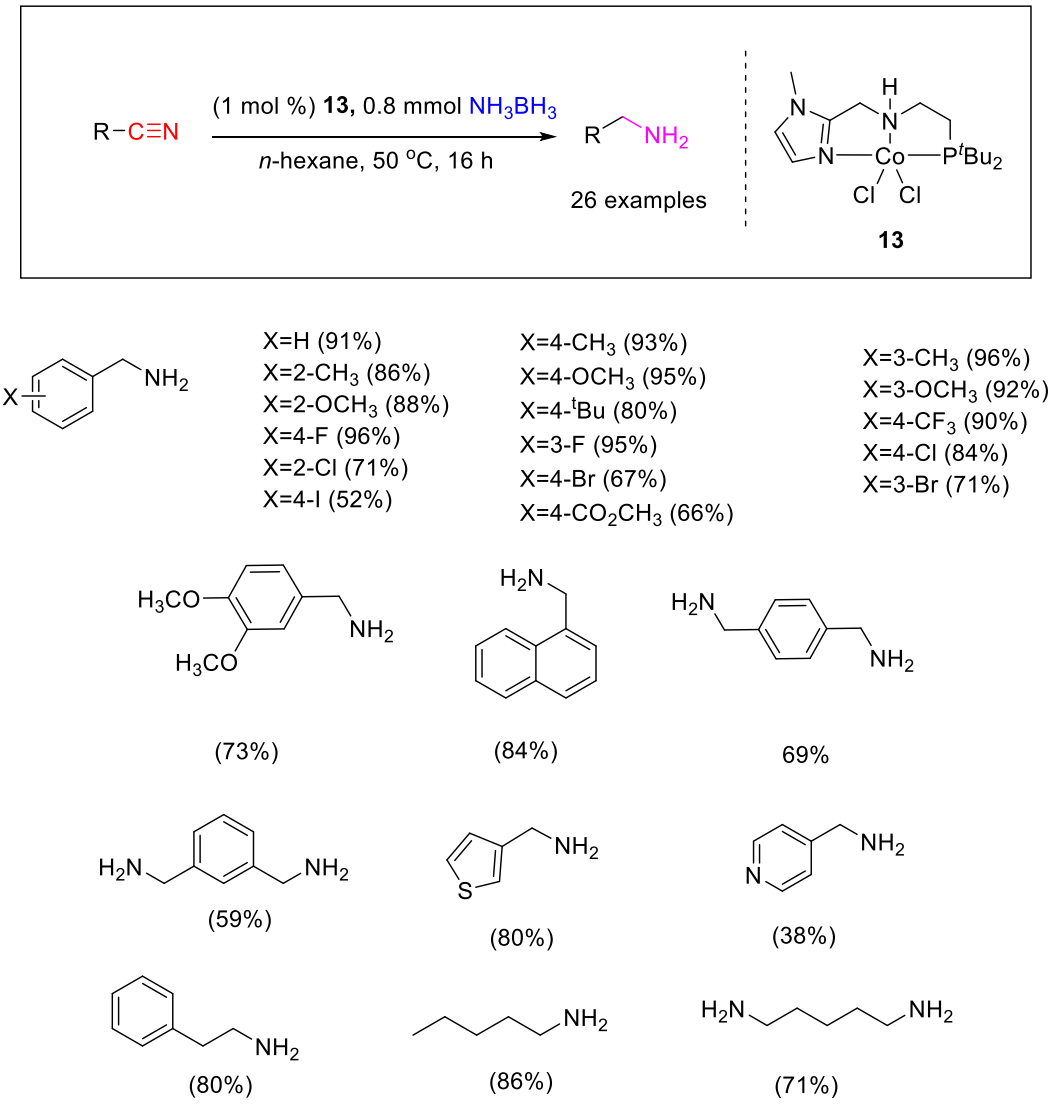
(99%)

2.2 Base metal-catalyzed transfer hydrogenation of nitriles

Despite the observed high catalytic activity of ruthenium complexes in TH reactions, the development of base metal systems for TH catalysis is highly desirable due to high natural abundance of base metals and their relatively lower toxicity. However, the examples of such catalysts are scarce.

Despite wide applications of cobalt compounds in catalysis, according to the literature, there is only one example of cobalt-catalyzed TH of nitriles to amines. In 2016, Liu *et al*. reported the selective and chemodivergent TH of nitriles with ammonia borane to either primary, secondary or tertiary amines catalyzed by cobalt (II) pincer complexes [15]. The selectivity of TH reactions was controlled by using different solvents and cobalt pre-catalysts. Noteworthy, the reactions did

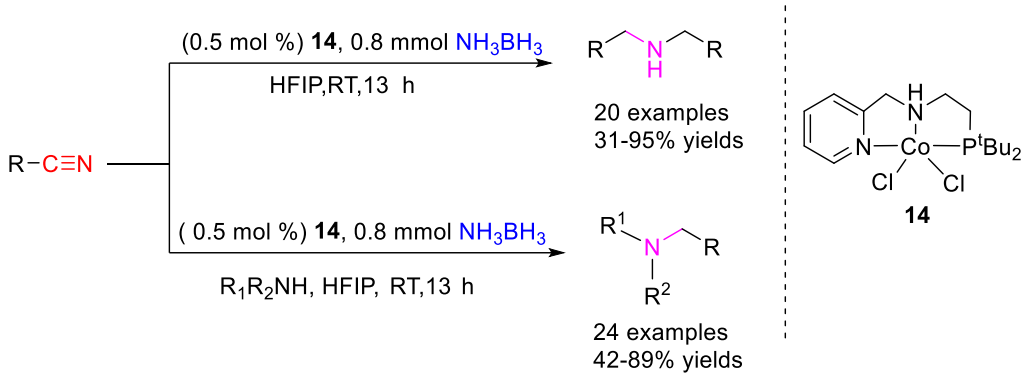
Scheme 13. 10-catalyzed TH of nitriles with ammonia borane to primary amines in *n*-hexane.



not require addition of the base and activation was achieved by ammonia borane. In *n*-hexane, using complex **13** as a pre-catalyst, the reactions afforded primary amine products (Scheme 13). The system was shown to be compatible with both aliphatic and aromatic nitriles having substituents of different electronic and steric properties and resulted in moderate-to-excellent yields of the corresponding primary amines. Moreover, ester and heteroaromatic functionalities (such as thiophene and pyridine) were well-tolerated under the experimental conditions.

As mentioned above, slight modifications in the catalyst structure and changing the solvent influences the outcome of Co-catalyzed TH reactions. Thus, using a pyridine-derived complex **14** and conducting the reactions in HFIP (hexafluoroisopropanol) allowed to obtain secondary amines as well as tertiary amines (when secondary amines were used as additives in TH of nitriles; Scheme 14). Efficient formation of secondary and tertiary amine products could be performed even at room temperature, using only 0.5 mol% of **14**.

Scheme 14. TH of nitriles with ammonia borane catalyzed by **14.**

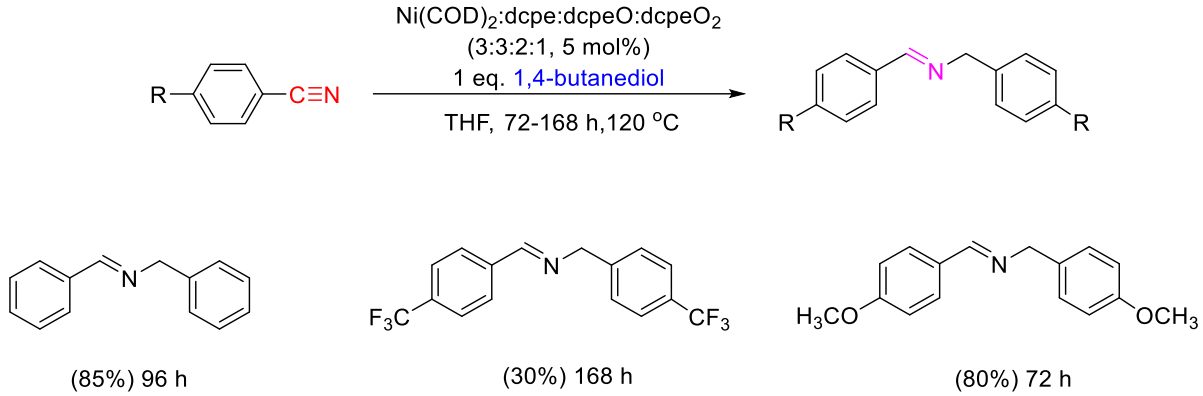


Analogously to cobalt, nickel-catalyzed TH of nitriles is limited to only one example demonstrated by García and Garduño in 2017 [13]. In this report, TH of nitriles was achieved using a mixture of $Ni(COD)_2$ precursor, dcpe, dcpeO, and $dcpeO_2$ (dcpe = 1,2-bis-(dicyclohexylphosphino)ethane; dcpeO = dcpe monoxide; $dcpeO_2$ = dcpe dioxide) in 3:3:2:1 ratio, respectively. The reactions were performed in THF in the presence of 1,4-butandieol as the hydrogen source and led to secondary imines. TH of benzonitrile was also tested with 2-propanol as the hydrogen source, but the reactions turned out to be non-selective. Overall, the scope of Ni-catalyzed TH of nitriles was rather narrow, and the reaction conditions were rather harsh (120 °C, up to 168 h; Scheme 15).

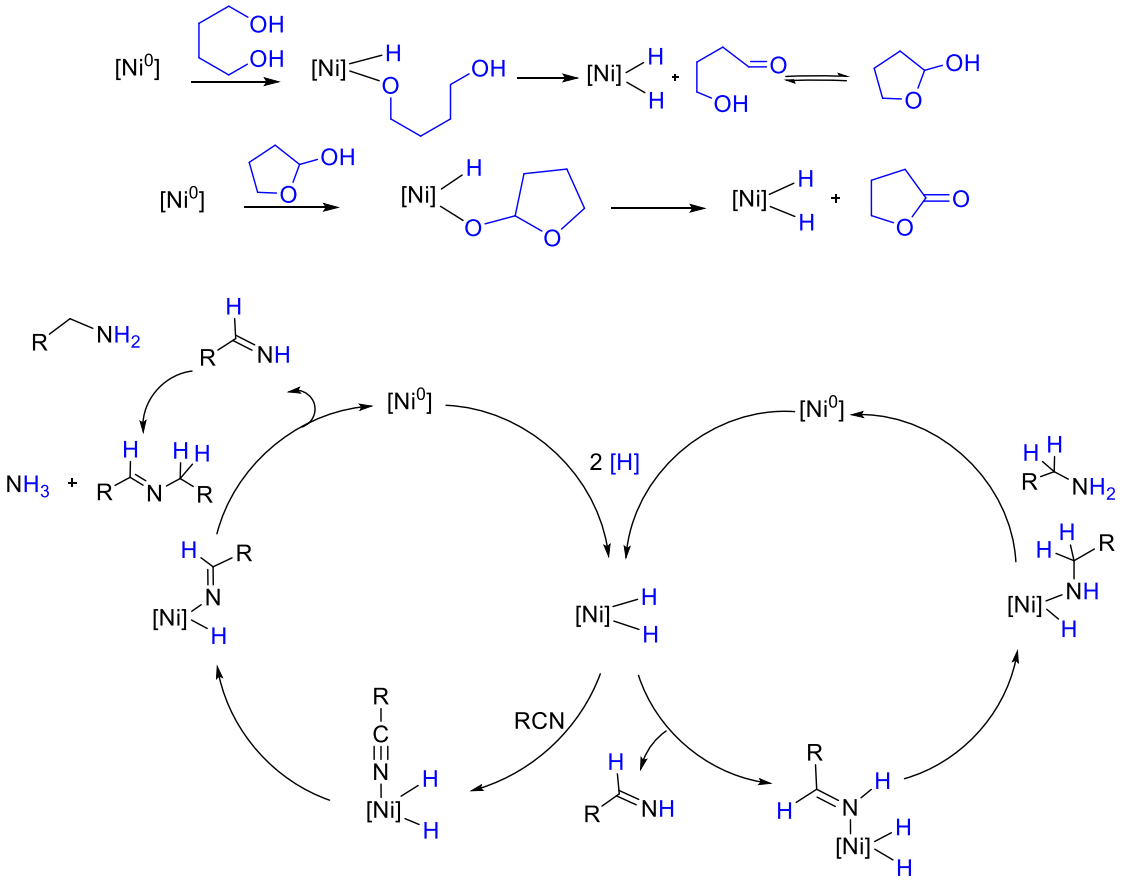
The proposed reaction mechanism for Ni-catalyzed TH of nitriles is depicted in Scheme 16 and starts with oxidative addition of 1,4-butanediol to Ni^0. This is followed by a *β*-hydrogen elimination to generate catalytically active Ni(II) hydride species, which first convert nitriles to

primary imines, followed by the reduction of the latter to primary amines. The formation of secondary imines was proposed to occur *via* the condensation of primary amine products with primary imine intermediates.

Scheme 15. $Ni(COD)_2$:dcpe:dcpeo:$dcpeO_2$-catalyzed TH of nitriles with 1,4-butanediol.



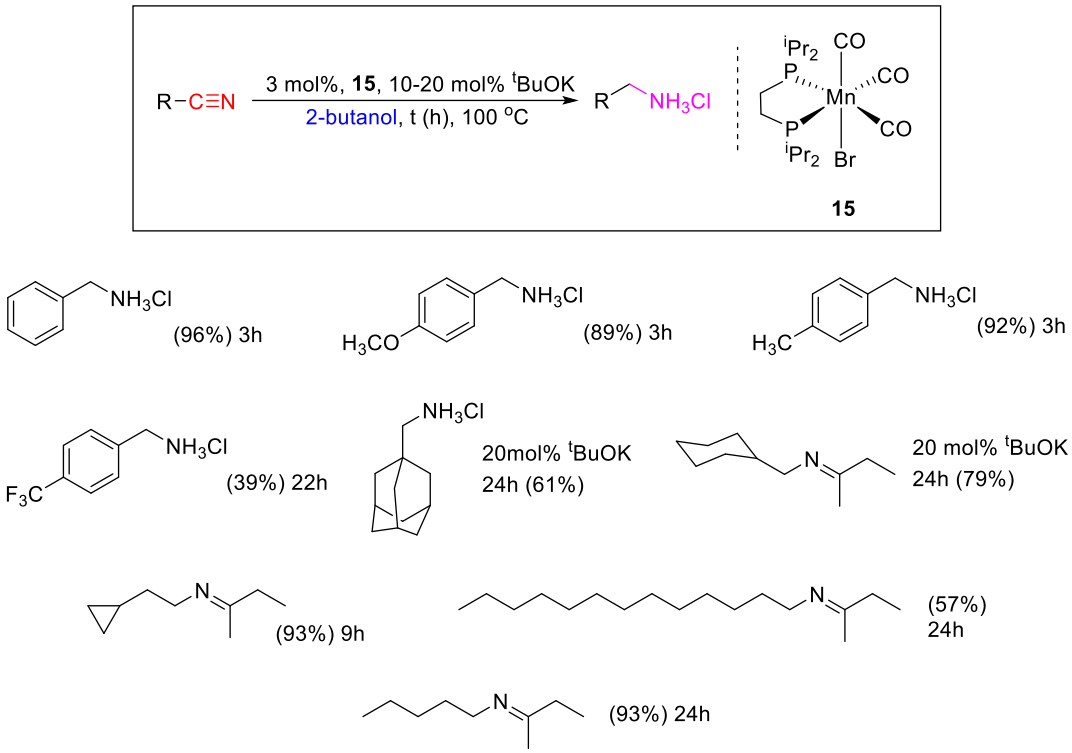
Scheme 16. The proposed mechanism of Ni-catalyzed TH of nitriles with 1,4-butanediol.



As mentioned before, manganese-catalyzed TH of nitriles is limited to only two works [24-25]. Thus, in 2019, García *et al.* reported the TH of nitriles with 2-butanol as the hydrogen source and a Mn(I) diphosphine carbonyl bromide complex **15** (Scheme 17) [24]. The reactions were performed at 100 °C using 3 mol% loading of the catalyst and 10 mol% of KO^{t}Bu as a base

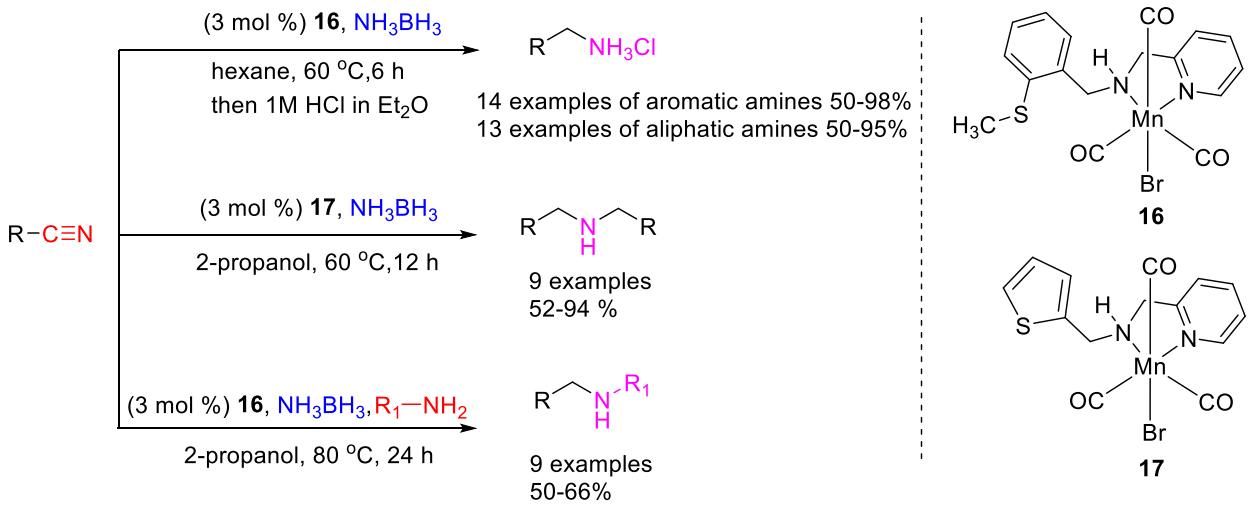
activator. For benzonitriles, formation of mixtures of benzylamines and N-*sec*-butylidenebenzylamines was observed. These mixtures were hydrolyzed with HCl to afford the corresponding ammonium salts. The scope of nitriles for **15**-catalyzed TH reactions is shown in Scheme 17. Notably, reduction of aliphatic substrates as well as benzonitriles with electron-withdrawing substituents turned out to be more challenging compared to benzonitriles with electron-donating functionalities.

Scheme 17. TH of nitriles with 2-butanol, catalyzed by Mn(I) complex **15**.



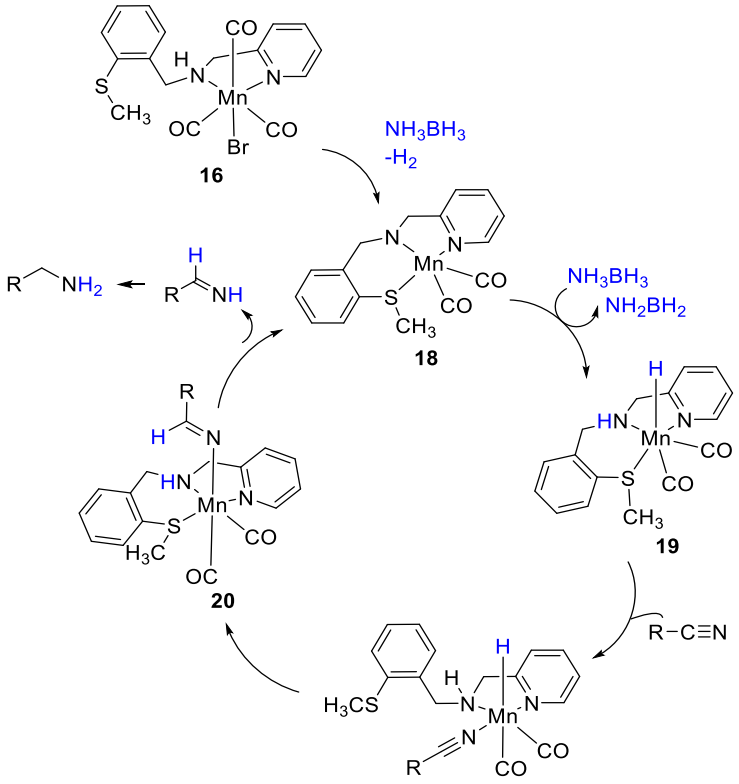
Finally, in 2021, Maji and co-workers reported the preparation of a series of phosphine free manganese(I) complexes and demonstrated their applications in TH of nitriles to primary, secondary and tertiary amines in the presence of ammonia borane as hydrogen source [25]. The unique feature of this systems, that it utilized hemilabile *S*- and *O*-containing ligands, that allow for stabilization of reactive catalytic intermediates. Complexes **16** and **17** with sulfur bearing ligands demonstrated the highest catalytic activity (Scheme 18). Thus, in *n*-hexane, in the presence of 3 mol% of **16** and 0.75 mol% of ammonia borane, different aromatic and aliphatic nitriles were reduced to the corresponding primary amines, which were isolated as their hydrochloride salts with moderate to excellent yields (50-98 %). Switching the solvent from *n*-hexane to 2-propanol allowed to shift the selectivity of reactions to secondary amines. More importantly, **16**-catalyzed TH of nitriles with ammonia borane in 2-propanol could be also performed in the presence of other primary amine additives to afford a series of non-symmetrical secondary amine products (Scheme 18).

Scheme 18. The scope of nitriles catalyzed by phosphine free Mn(I) complexes.



The proposed mechanism for **16**-catalyzed TH reactions is depicted in Scheme 19 and involves an outer sphere dehydrogenation of ammonia borane, followed by an inner sphere hydrogen transfer to nitrile. The catalytic cycle starts with an amido complex **18**, having sulfur side arm of the ligand coordinated to Mn and formed *via* transmetallation of the complex **16** with ammonia borane and the release of dihydrogen. The amide **18** is conversed to the hydride amino species **19** *via* dehydrogenation of ammonia borane. This is followed by the dissociation of the sulfur ligand side-arm and coordination of the nitrile, which then undergoes migratory insertion into the Mn-H bond to give an imide intermediate **20**. The release of an imine from the latter complex recovers the amide catalyst **18**. The imine product is then either subjected to the second TH cycle to form an amine or undergoes condensation with primary amine to give a secondary imine intermediate (see the reaction depicted in Scheme 2), which is then hydrogenated to the corresponding secondary amine. Notably, a thioether side arm of the ligand in **16** plays and important role stabilizing reactive manganese intermediates throughout the catalytic cycle. An analogous mechanism could be also proposed for **17**-catalyzed transformations.

Scheme 19. TH of nitriles of nitriles catalyzed by Mn-SNN complex **16**.

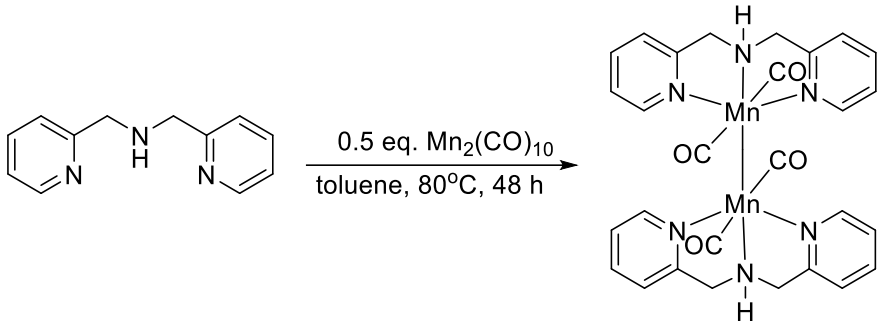


3 Results and Discussion

3.1 Synthesis and characterization of Mn complexes:

We started our investigation with either commercially available or easily accessible ligands bearing secondary amine functionalities. First, the Mn(0) precursor, $Mn_2(CO)_{10}$, was treated with commercial dipicolylamine (DPA) to produce a diamagnetic Mn(0) species. Considering that Mn(0) has 7 valence electrons, formation of a diamagnetic complex is possible only in the case of dinucclear derivatives, containing a Mn-Mn bond. Based on the NMR analysis of the product of this reaction and comparison of the NMR features of the free ligand *vs.* the product, formation of a dimeric species, featuring a single Mn-Mn bond akin to complex **21** in Scheme 20, was suggested. However, further elucidation of the structure of **21** by the single crystal X-ray diffraction analysis is necessary and will be performed in a due course.

Scheme 20. The synthesis of Mn(0) complex **21**.

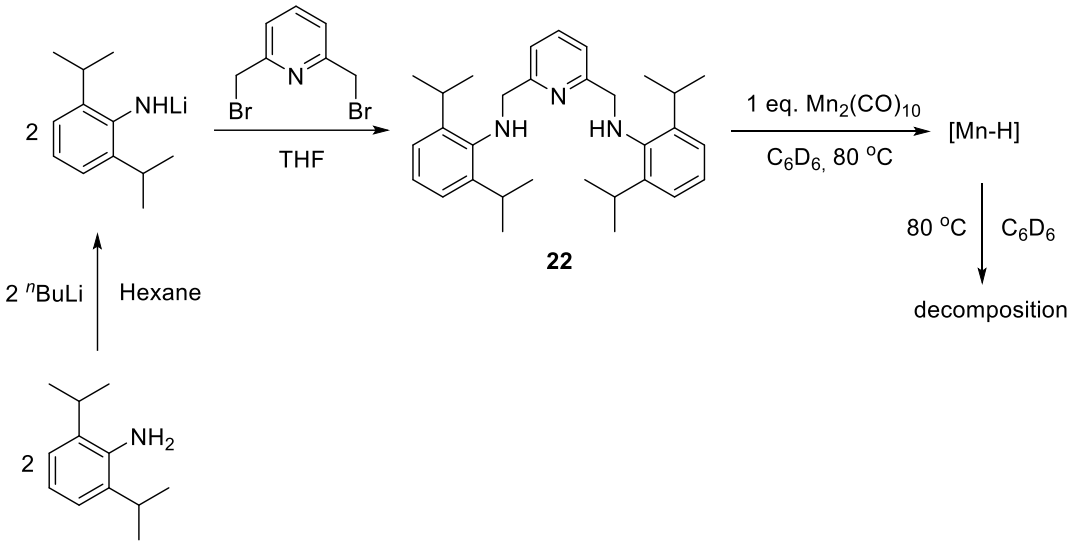


21

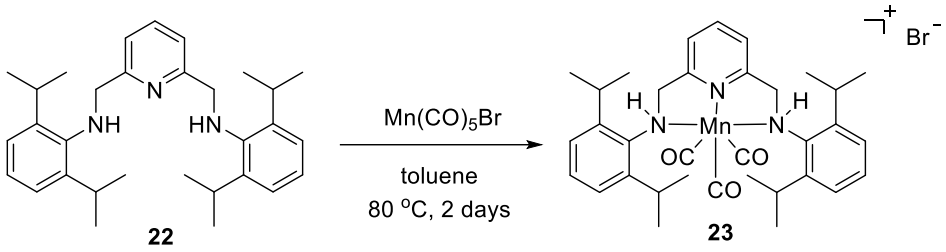
Similarly, $Mn_2(CO)_{10}$ was reacted with *N,N′*-(pyridine-2,6-diylbis(methylene))bis(2,6-diisopropylaniline) (**22**) ligand prepared by the literature route based on the reaction of lithium 2,6-diisoprobylanilide with 2,6-bis(bromomethyl)pyridine (Scheme 21) [33]. The metalation reaction was performed at 80 °C in C_6D_6 and was followed by NMR, which showed the initial formation of small amounts of a metastable manganese hydride species (δ_H = -7.90 ppm for Mn-H resonance), likely formed by the oxidative addition of the N-H moiety of the ligand to Mn(0) center. The exact structure of this initial product remains unknown, and all attempts to increase its concentration in the reaction mixture and/or further characterize the product by spectroscopic techniques were unsuccessful due its low concentration and its thermal instability. Thus, further heating the reaction at 80 °C for additional two days resulted in slow decomposition of the observed hydride species to a mixture of unidentified compounds.

In contrast, switching from Mn(0) to Mn(I) precursor, $Mn(CO)_5Br$, in the reaction with the ligand 22 allowed to obtain a cationic complex **23** (Scheme 22). The reaction was done in toluene at 80 °C, and the product precipitated from the reaction mixture after 2 days of heating. The product was characterized by NMR, suggesting a monomeric structure of **23** with the Mn center bearing three CO ligands. Unlike in the case of Mn(0), no hydride species were detected in this case.

Scheme 21. Preparation of N,N'-(pyridine-2,6-diylbis(methylene))bis(2,6-diisopropylaniline) ligand and its reaction with $Mn_2(CO)_{10}$.



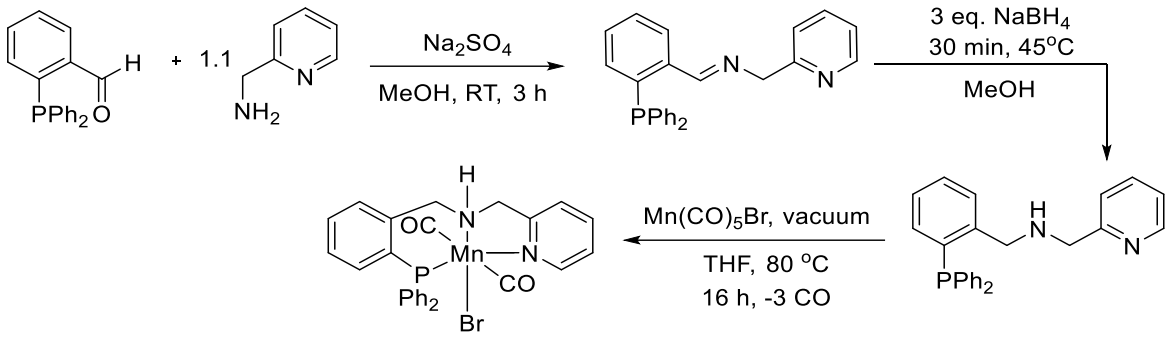
Scheme 22. The synthesis of Mn(I) complex **23**.



Aiming to prepare neutral Mn(I) complexes, the next part of the project was based on the application of less sterically hindered (compared to **22**) pincer type ligands for the preparation of bifunctional Mn(I) complexes with a secondary amino functionality in the bridge-head position of the ligand. For the concept testing purposes, we targeted the preparation of the PN^HN complex **24** (Scheme 23), application of which in catalytic hydrogenation of esters and lactones was previously reported by Zhou *et al*. [35] and Schaub *et al*. [34]. The synthetic route to **24** is depicted in Scheme 23. The synthesis of the PN^HN ligand was achieved based on the literature procedure reported by Rigo *et al.* (2007) [36] and involved the condensation of commercially available 2-(diphenylphosphino)benzaldehyde with 2-picolylamine to give an imine intermediate, followed by the reaction with $NaBH_4$ to afford the target secondary amine PN^HN ligand (Scheme 23). The

subsequent ligand metalation reaction with $Mn(CO)_5Br$ was performed in vacuum (to ensure efficient removal of 3 CO ligands; see experimental part for details) in THF at 80 °C and resulted in 64% yield of $(PN^HN)Mn(Br)(CO)_2$ (**24**; Scheme 23). All NMR features of the isolated complex **24** are consistent with those previously reported in the literature (see the experimental part for details) [34].

Scheme 23. Synthesis of $(PN^HN)Mn(Br)(CO)_2$ **(24).**



24

An analogous approach was also used for the preparation of the bifunctional Mn(I) complex **25**, bearing a bidentate aminophosphine PN^H ligand. Although the ligand synthesis was previously described by Zhou *et al.* [35] and could be easily prepared by the reductive amination of 2-(diphenylphosphino)benzaldehyde with aniline and $NaBH(OAc)_3$ (Scheme 24), no preparation of Mn complexes with this ligand has been previously disclosed. Interestingly, the reductive amination step was found to be highly sensitive to the concentration of the reaction mixture, showing higher conversions to the desired aminophosphine ligand only in more concentrated solutions. The ligand metalation step was performed analogously to the synthesis of complex **24** and resulted in 64% yield of $(PN^H)Mn(Br)(CO)_3$ (**25**, Scheme 24), which was fully characterized by NMR and X-ray diffraction analysis.

First, the complexation of PN^H ligand was evident from the ^{31}P-NMR spectrum of **25**, which, compared to free PN^H ligand, showed a downfield ^{31}P resonance at δ 38.3 ppm (*vs.* δ_P = -15.7 ppm for free PN^H). Complexation of the nitrogen side arm of the PN^H ligand to Mn in **25** also resulted in the downfield shift of the NH proton resonance (found at δ 4.49 ppm) compared to NH proton resonance in free PN^H (found at δ 3.92 ppm). Apart from NMR, formation of complex **25.** was also confirmed by single crystal X-ray diffraction analysis, which was recorded using a single crystal obtained from CH_2Cl_2 solution of **25** by slow evaporation of CH_2Cl_2 into THF at room temperature. The molecular structure of complex **25** is depicted in Figure 2. The selected bond distances and bond angles for **25** are listed in Table 2, and the X-ray analysis parameters can be found in the experimental section. Complex **25** adopts an octahedral geometry with the PN^H ligand

occupying equatorial position and the bromide ligand occupying apical position resulting in the Mn-Br and N-H moieties oriented cis- relative to each other. Three other positions, two equatorial and one apical, are occupied with three CO ligands. Such octahedral geometry and relative orientation of the N-H and Mn-Br fragments in **25** is consistent with other structurally characterized aminophosphine Mn(I) bromides previously reported in the literature [34].

Scheme 24. Synthesis of $(PN^{H})Mn(Br)(CO)_3$ **(25)**.

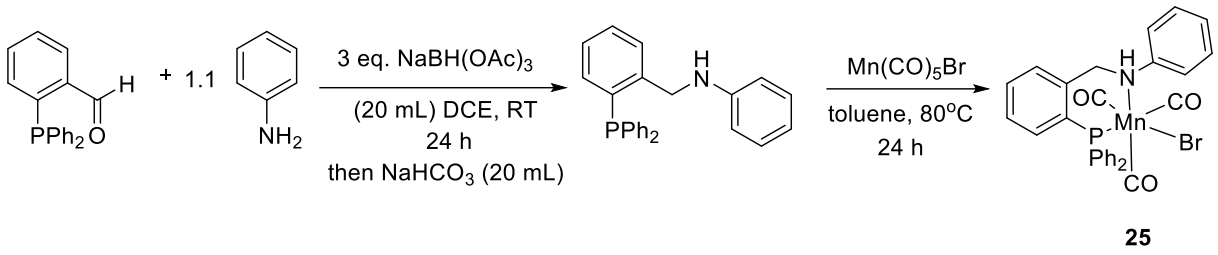


Figure 2. Molecular structure of complex **25**.

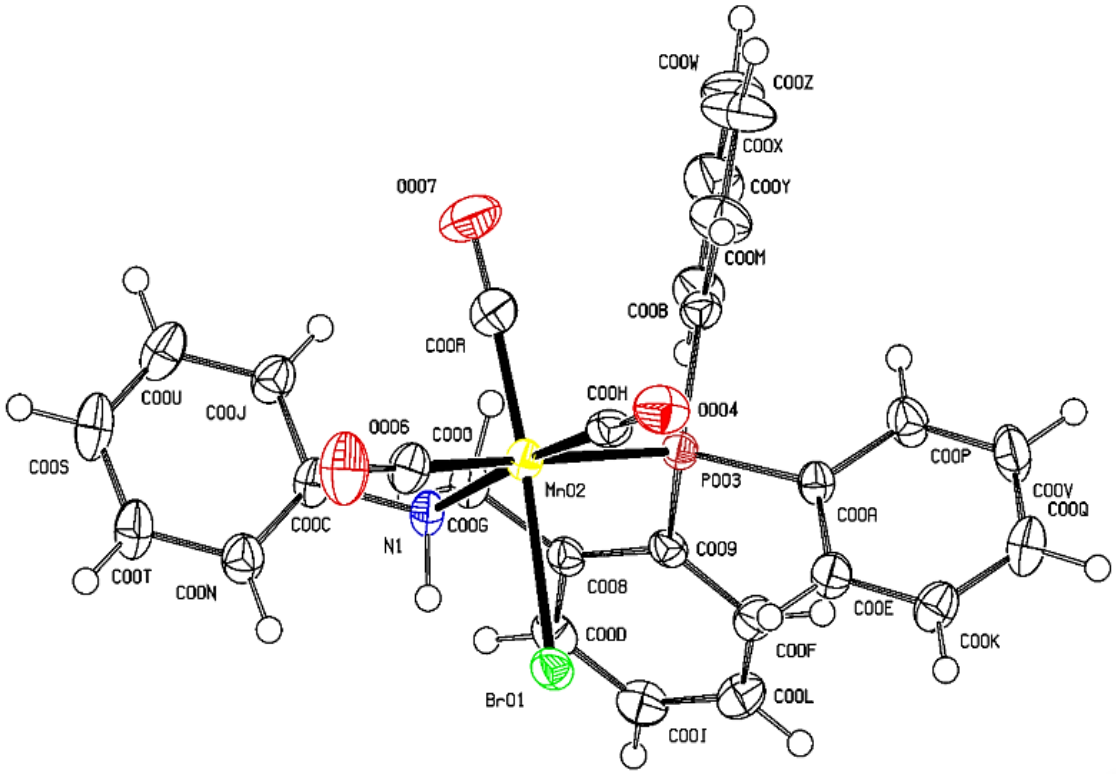


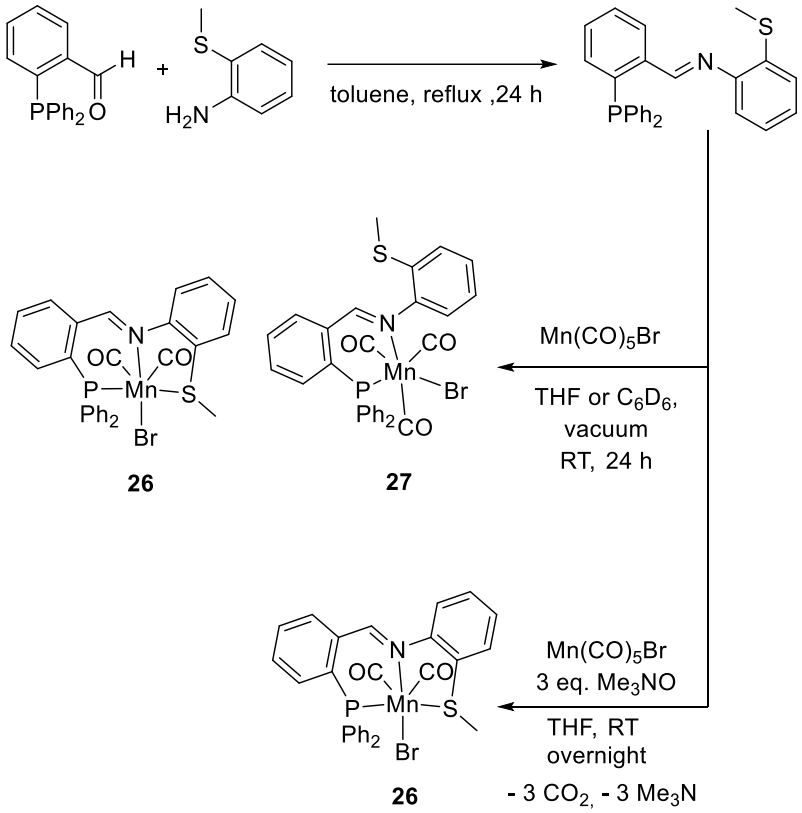
Table 1. Bond distances (Å) and bond angles (º) for complex **25**.

Bond distances (Å)		Bond angles (º)	
Mn02-Br01	2.5190(7)	P003-Mn02-Br01	91.46(3)
Mn02-P003	2.3532(10)	N1-Mn02-Br01	84.69(9)
Mn02-N1	2.169(3)	N1-Mn02-P003	89.81(8)
Mn02-C00H	1.794(4)	C00H-Mn02-Br01	90.10(12)
Mn02-C00O	1.833(4)	C00H-Mn02-P003	89.43(13)
Mn02-C00R	1.797(4)	C00H-Mn02-N1	174.71(16)
P003-C009	1.823(4)	C00H-Mn02-C00O	87.24(18)
P003-C00A	1.830(4)	C00H-Mn02-C00R	92.38(18)
P003-C00B	1.833(4)	C00O-Mn02-Br01	87.20(14)
N1-C00C	1.452(5)	C00O-Mn02-P003	176.41(13)
N1-C00G	1.499(4)	C00O-Mn02-N1	93.39(15)
O004-C00H	1.150(5)	C00R-Mn02-Br01	175.58(14)
O006-C00O	1.138(5)	C00R-Mn02-P003	92.22(13)
O007-C00R	1.149(5)	C00R-Mn02-N1	92.88(16)
		C00R-Mn02-C00O	89.27(19)

Inspired by the report of Maji *et al.* on application of hemilabile NNS Mn(I) complexes in TH of nitriles [25], we intended to test this concept with our diphenylphosphino ligands. For this, the $PN^{imine}S$ ligand was synthesized from 2-(diphenylphosphino)benzaldehyde by its condensation reaction with 2-(methylthio)aniline (Scheme 25). Initially, the metalation of this ligand with $Mn(CO)_5Br$ was attempted using the reaction conditions analogous to the synthesis of **24** (see Scheme 23). However, in this case, the rection afforded a mixture of two products, characterized by two very distinct ^{31}P resonances in the ^{31}P-NMR spectrum (δ_P = 77.63 ppm and δ_P = 47.83 ppm, compare with δ_P = -14.03 ppm for free $PN^{imine}S$ ligand). Notably, these ^{31}P chemical shifts are very similar to those, observed for the previously described Mn(I) complexes, $(PN^{H}N)Mn(Br)(CO)_2$ (**24**; δ_P = 72.26 ppm) and $(PN^{H})Mn(Br)(CO)_3$ (**25**; δ_P = 38.27 ppm). Based on these observations and considering the hemilabile behavior of analogous $NN^{H}S$ ligands, previously reported by Maji *et al.* [25], the observed ^{31}P resonances were tentatively assigned to κ^2- and κ^3-$PN^{imine}S$ derivatives, δ_P = 77.63 ppm for (κ^3-$PN^{imine}S$)$Mn(Br)(CO)_2$ (**26**) and δ_P = 47.83 ppm for (κ^2-$PN^{imine}S$)$Mn(Br)(CO)_3$ (**27**) (Scheme 25). To test this suggestion, the reaction of $PN^{imine}S$ ligand with $Mn(CO)_5Br$ was repeated in THF the presence of 3 equivalents of Me_3NO as CO trapping agent, resulting in the selective formation of a product characterized by the ^{31}P resonance at δ_P = 77.63 ppm in its ^{31}P-NMR spectrum. Only trace amounts of the second product with δ_P = 47.83

ppm were detected by NMR. Therefore, we suggest that added Me_3NO irreversibly reacts with 3 equivalents of CO to give Me_3N and CO_2, thus, shifting the equilibrium towards formation of the κ^3-PN^{imine}S complex **26**, bearing only two CO ligands at Mn (Scheme 25). Considering potential hemilabile behavior of the S-side arm of the PN^{imine}S ligand, as well as the presence of only two CO ligands in **26**, this system could potentially exhibit higher activity in catalytic TH reactions compared to Maji's complex (κ^3-NNS)Mn(Br)(CO)$_3$ [25], resulting in less coordinatively saturated and hence more catalytically active species, akin to (κ^2-PN^{imine}S)Mn(Br)(CO)$_2$, produced by the cleavage of the relatively weak Mn-S bond.

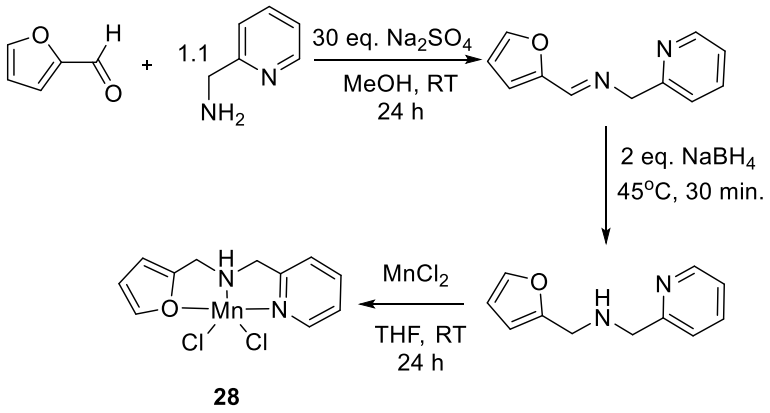
Scheme 25. Preparation of PN^{imine}S ligand and its Mn(I) complexes **26** and **27**.



Finally, the preparation of Mn(II) complexes was studied. Due to the well-recognized air sensitivity and toxicity of phosphines, in this part of the project, the focus was made on the application of phosphine-free ligands. Since we intended to utilize neutral ligands and since metalation of such ligands with Mn(II) precursors (akin to $MnCl_2$) would result in complexes with two anionic ligands at Mn, we thought of developing the phosphine-free ligand system having a hemilabile side arm, amenable of creating an additional coordination site at Mn(II) centers. The availability of such coordination sites is crucial for catalytic applications of the target complexes, allowing for substrate coordination to the metal center during the catalysis. As mentioned above, similar hemilabile ligands having weakly coordinating O- and S-donors in the ligand side arms

have been previously developed by Maji *et al.* and applied in Mn(I)-catalyzed TH of nitriles [25] Considering higher stability of Mn(II) compounds compared to Mn(I) compounds [37], the development of hemilabile Mn(II) systems could potentially increase the robustness of TH pre-catalysts (for example, in terms of air-senility), while maintaining their high catalytic activity. Keeping this in mind, an NN^HO ligand was synthesized by the condensation of furan-2-carbaldehyde with 2-picolylamine, followed by the reduction of the produced imine with $NaBH_4$ [25]. The subsequent reaction of NN^HO ligand with $MnCl_2$ in THF afforded a Mn(II) complex, $(NN^HO)MnCl_2$ (**28**; Scheme 26). Formation of the target product was suggested based on monitoring the reaction by ^{1}H-NMR, which revealed the disappearance of the proton resonances for the NN^HO ligand and generation of a paramagnetic compound, consistent with the κ^3-coordination of the NN^HO ligand to Mn to give a 5-coordinate 15e species **28** as depicted in Scheme 26.

Scheme 26. Synthesis of NN^HO ligand and its Mn(II) complex, $(NN^HO)MnCl_2$ **(28).**

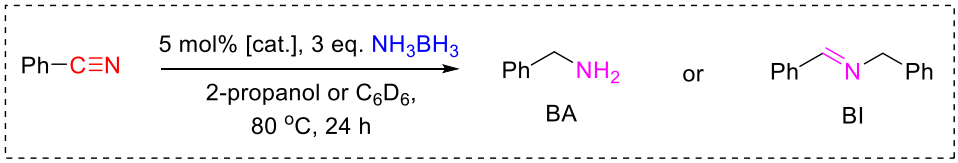


3.2 Mn-catalyzed transfer hydrogenation of nitriles

Having the target pre-catalysts in hand, we performed testing of their catalytic activity in TH of nitriles using ammonia borane as the hydrogen source. Considering the previously reported examples of Mn-catalyzed TH reactions [24,25], we started our catalytic studies with Mn(I) complexes, but then moved to Mn(II) derivatives. Benzonitrile was chosen as a model substrate and its reduction with ammonia borane was attempted using 5 mol% of $[(N^HNN^H)Mn(CO)_3]Br$ (**23**), $(PN^HN)Mn(Br)(CO)_2$ (**24**), $(PN^H)Mn(Br)(CO)_3$ (**25**) and $(NN^HO)MnBr_2$ (**28**) as pre-catalysts. The reactions were performed either in C_6D_6 or in 2-propanol at 80 °C for 24 h, and the results of these trials are summarized in Table 2. It should be noted that the yields of benzylamine reported herein correspond to the isolated yields of the $[PhCH_2NH_3]Cl$ salt, produced by the treatment of the reaction mixture with HCl in Et_2O (see the experimental part for details).

First, TH of PhCN with NH_3BH_3 in 2-propanol was attempted in the presence of 5 mol% of complex **23**, but the reaction resulted only in trace amounts of benzylamine (Table 2, entry 1). Such low catalytic activity of **23** is likely associated with the presence of the sterically hindered ligand, preventing deprotonation of the ligand side arm. In contrast, using 5 mol% of the PN^HN derivative **24**, the reaction in 2-propanol resulted in selective formation of the secondary imine product, instead of the expected benzylamine (Table 2, entry 2). Although the yield of the imine was not determined at this point, no primary amine product was detected by ^{1}H-NMR. Interestingly, switching to either PN^H Mn(I) or NN^HO Mn(II) pre-catalysts **25** and **28** resulted in no conversion of PhCN (Table 2, entries 3 and 4), presumably due to very low solubility of these manganese complexes in 2-propanol.

Table 2. The transfer hydrogenation of benzonitrile with NH_3BH_3 catalyzed by **23-27** complexes.



entry	catalyst	solvent	product[a]	yield
1	**23**	2-propanol	BA	traces
2	**24**	2-propanol	BI	5 %
3	**25**	2-propanol	NR[b]	—
4	**28**	2-propanol	NR[b]	—
5	**24**	C_6D_6	BA	90 %
6	**25**	C_6D_6	BA	95 %
7	**28**	C_6D_6	BA	87 %

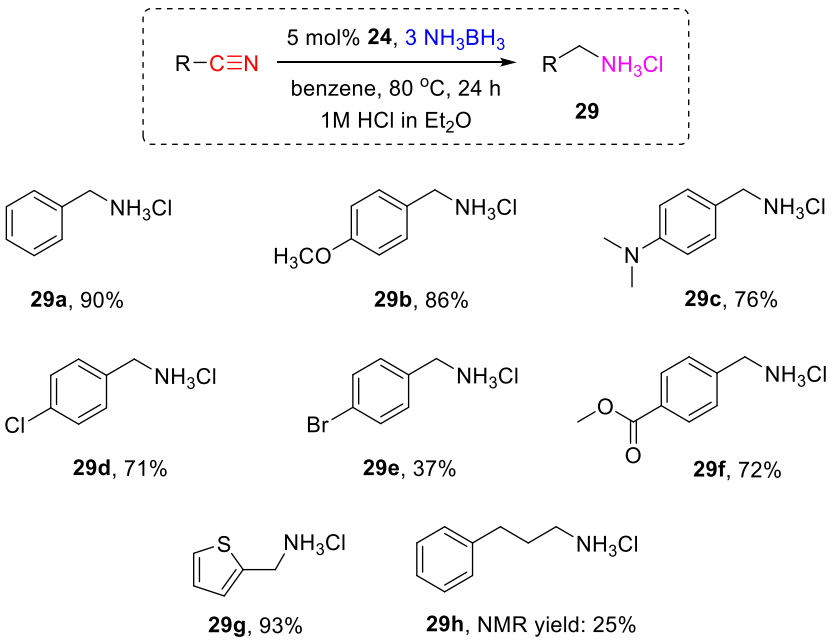
[a] Benzylamine was converted to its hydrochloride salt by the addition of HCl in Et_2O. The reported yield is the yield of isolated hydrochloride salt.
[b] NR = no reaction.

Having no success in TH of nitriles to amines in 2-propanol, the solvent was changed to C_6D_6, in which all complexes (**24**, **25** and **28**) except the cationic species **23** were well-soluble. To our delight, conducting **24**-catalyzed (5 mol%) TH of PhCN with NH_3BH_3 in C_6D_6 at 80 °C resulted in complete conversion of benzonitrile and exclusive formation of benzylamine, which was *in situ* converted to its hydrochloride salt and isolated with 90% yield (Table 2, entry5). An analogous reaction with 5 mol% of **25** bearing bidentate PN^H ligand afforded 95% of

[$PhCH_2NH_3$]Cl (Table 2, entry 6), whereas **28**-catalyzed reaction yielded 87% of TH product (Table 2, entry 7). Such deviations in the yield of benzylamine hydrochloride between **24**-, **25**- and **28**-catalyzed TH of PhCN are insignificant and could be associated with statistical losses of small amounts of the product during its isolation. However, due to steric considerations, the PN^H complex **25** is expected to perform somewhat better in TH reactions compared to its pincer type analogues **26** and **28**.

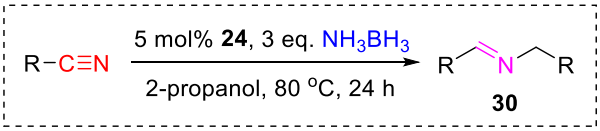
Having active pre-catalysts **24**, **25** and **28** in hand, the scope of TH of nitriles with ammonia borane was tested. First, the PN^HN Mn(I) complex **24** was tried out, and the results of these tests are summarized in Scheme 27. Thus, **24**-catalyzed TH of aromatic nitriles turned out to be more efficient compared to aliphatic substrates (compare **29a-g** with **29h**; Scheme 27). Benzonitriles having both electron-donating and electron-withdrawing functionalities resulted in good isolated yields of the corresponding ammonium salts (71-93%). The system was found to be chemoselective towards CN reduction in the presence of aryl chlorides, ester and thiophene functionalities (see **29d**, **29f** and **29g**). However, rather low yield of the *para*-bromobezylamine hydrochloride (37%, **29e**, Scheme 27) was detected upon **24**-catalyzed TH of 4-bromobenzonitrile. In contrast, the analogous reaction with 4-chlorosubstituted derivative resulted in 71% yield of the corresponding ammonium salt (**29d**, Scheme 27). Such lack of reactivity of 4-bromobenzonitrile compared to 4-chlorobenzonitrile could be rationalized by possible concurrent hydrodebromination of 4-bromobenzonitrile, which is often observed under catalytic reduction conditions [16]. Such C-Br bond cleavage of 4-bromobenzonitrile would lead to deactivation of the catalyst, resulting in the low yield of the product of CN reduction.

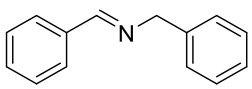
Scheme 27. 24-catalyzed TH of nitriles with NH_3BH_3 to primary amines in benzene.



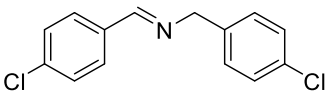
As mentioned before, switching the solvent from C_6D_6 to 2-propanol affects the selectivity of TH reactions. Scheme 28 illustrates the results of **24**-catalyzed TH of benzonitrile, 4-chlorobenzonitrile and 4-(dimethylamino)benzonitrile with NH_3BH_3 in 2-propanol. Interestingly, both benzonitrile and 4-chlorobenzonitrile resulted in formation of only small amounts of secondary imine products (**30a** and **30b**), as the result of the condensation of the primary imine intermediate RC(H)=NH with the primary amine product RCH_2NH_2 (R = Ph; *p*-ClC_6H_4) (for the description of this condensation reaction, see Scheme 2). However, substitution of benzonitrile with electron-donating functionalities (such as *p*-Me_2N and *p*-MeO) diminishes this reactivity, and no formation of secondary imine products was observed, presumably due to decreased electrophilicity of the imine carbon of the primary imine intermediate. Instead, for 4-(dimethylamino)benzonitrile, the reaction resulted in the primary amine product with 52 % yield (determined by ^{1}H-NMR using 1,3,5-trimethoxybenzene as internal standard). Surprisingly, in the case of 4-methoxybenzonitrile neither secondary imine no primary amine products were detected by NMR. At this point, we do not have any reasonable explanation of such a lack of reactivity of 4-methoxybenzonitrile compared to 4-(dimethylamino)benzonitrile, and more detailed investigations are necessary to understand this phenomenon.

Scheme 28. 24-catalyzed TH of nitriles with NH_3BH_3 in 2-propanol.

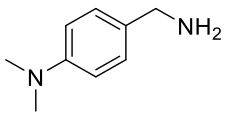




30a
NMR yield 5%



30b
NMR yield: 8%



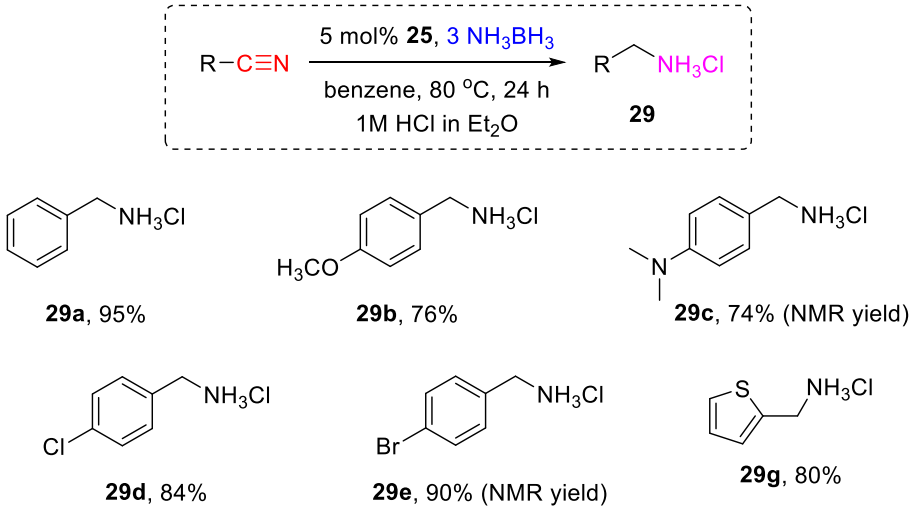
31c
NMR yield: 52%

To compare the reactivities of the Mn(I) PN^HN pincer pre-catalyst **24** and the Mn(I) PN^H derivative **25**, complex **25** was subjected to TH reactions of a series of aromatic nitriles with electron-donating and electron-withdrawing functionalities (Scheme 29). Due to poor solubility of **25** in 2-propanol resulting in no conversion of nitriles (see Table 2, entry 3), **25**-catalyzed TH of nitriles was tested only in C_6D_6. Similarly, to pincer complex **24**, **25**-catalyzed reactions resulted in exclusive formation of primary amine products, which were isolated as their hydrochloride salts in good yields (74-95%). Overall, the reactions worked equally well for electron-deficient and electron-rich aromatic amides and the observed yields of amines were somewhat similar to those for **24**-catalyzed transformations. Surprisingly, 4-bromobenzonitrile, which poorly performed in TH catalyzed by complex **24**, resulted in 90% of the hydrochloride salt upon **25**-catalyzed protocol.

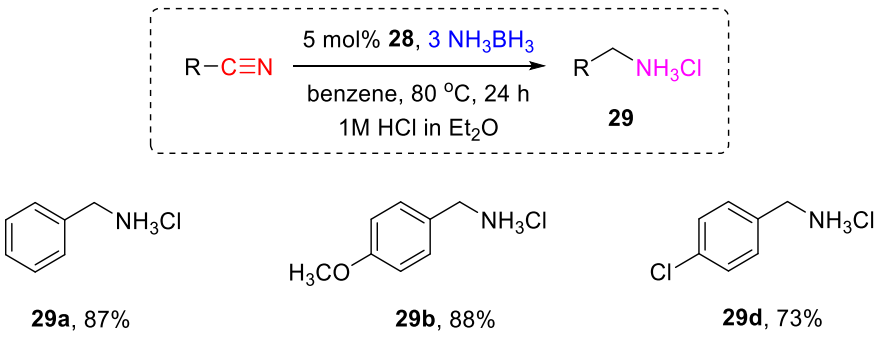
The origin for such an improved reactivity of 4-bromobenzonitrile towards CN reduction *vs.* hydrodebromination could be rationalized by the kinetic control of the reaction, i.e. less sterically crowded complex **25** (compared to **24**) could allow for faster hydrogen transfer to CN.

Finally, the TH of several benzonitriles was attempted with $NN^{H}O$ Mn(II) pre-catalyst **28**. Similarly, to complex **25**, **28** showed poor solubility in 2-propanol, restricting its catalytic application to only C_6D_6. Three benzonitriles with different electronic properties were tested (benzonitrile, 4-methoxybenzonitrile and 4-chlorobenzonitrile) showing exclusive formation of primary amines (Scheme 30). The yields of the isolated ammonium salts are very similar to those previously discussed for **24**- and **25**-catalyzed reactions (compare **29a,b,d** in Schemes 27, 29 and 30); albeit the advantage of pre-catalyst **28** could be in its lower air-sensitivity.

Scheme 29. 25-catalyzed TH of aromatic nitriles with NH_3BH_3 to primary amines in benzene.



Scheme 30. 28-catalyzed TH of nitriles with NH_3BH_3 to primary amines in benzene.

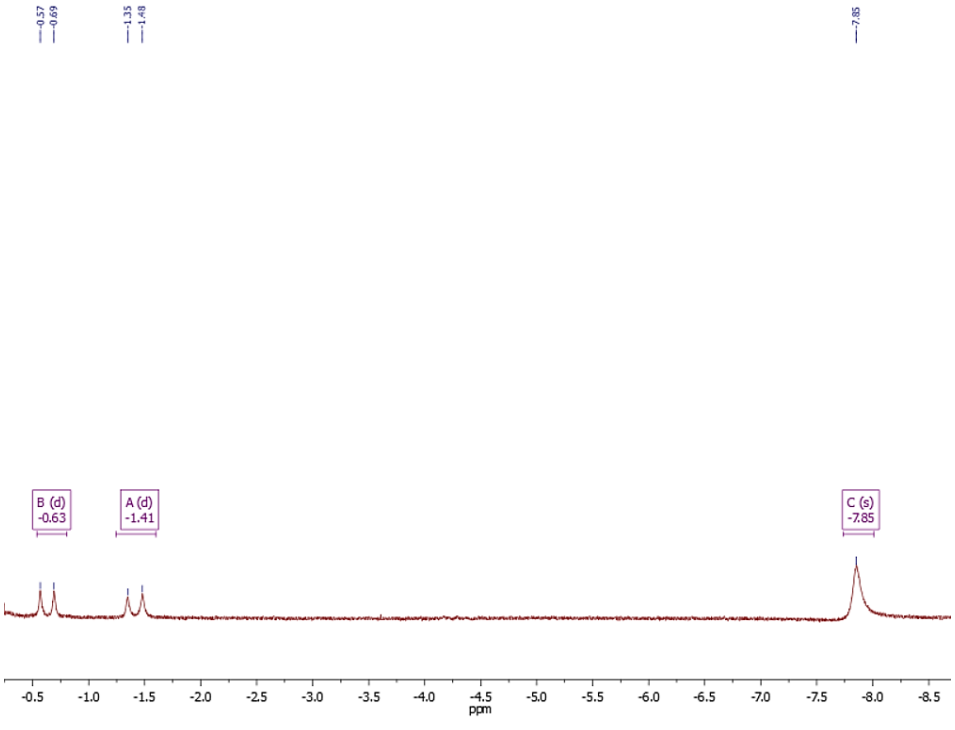


3.3 Mechanistic aspects of Mn-catalyzed transfer hydrogenation reactions

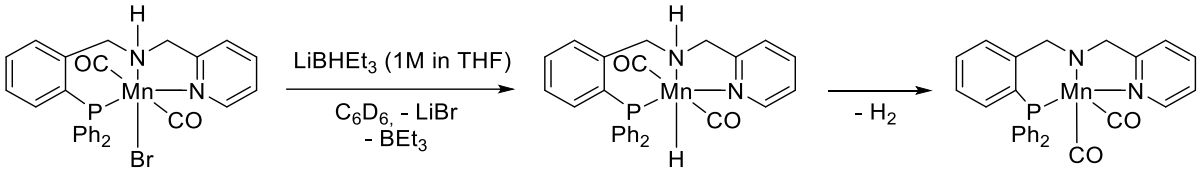
To get some insights into the nature of catalytically active species in TH reactions we studied the reactivity of complexes **24** and **25** with $LiBHEt_3$ to generate the hydride derivatives. In this regard, complex **24** was treated with 1.1 equivalents of $LiBHEt_3$ in C_6D_6 directly in an NMR tube, and the reaction was monitored by NMR spectroscopy at room temperature. In 30 min at room temperature after addition of $LiBHEt_3$, formation of a mixture of hydride species was observed (Figure 3). The reaction was left at room temperature for 48 h, resulting in the observation of the only manganese-bound hydride resonance at δ -7.85 ppm in the ^{1}H-NMR spectrum. However, the concentration of this species in the mixture was too small for its complete NMR characterization, and all attempts to drive the reaction towards increased conversions of **24** to this hydride were unsuccessful. The observed hydride species was found to be metastable and decomposed in solution at room temperature with the liberation of H_2 (δ 4.47 (s) in C_6D_6 [38]) to give a mixture of unidentified products. These observations, together with the literature precedents for the reactivity of analogous Mn(I) complexes [25], allowed us to tentatively assign the hydride product to $(PN^HN)Mn(H)(CO)_2$ (**32**; Scheme 31), which in the absence of the nitrile substrate decomposes *via* the release of H_2 to give the corresponding coordinatively unsaturated amide complex $(PN^HN)Mn(CO)_2$ (**33**), also unstable under stoichiometric reaction conditions.

Figure 3. The hydride region of the ^{1}H-NMR spectrum taken directly from the reaction of complex **24** with $LiBHEt_3$ in C6D6 after 30 min at room temperature.

δ -0.63 (d, *J* = 61.5 Hz, Mn*H*), -1.41 (d, *J* = 65.7 Hz, Mn*H*), -7.85 (s, 2H).



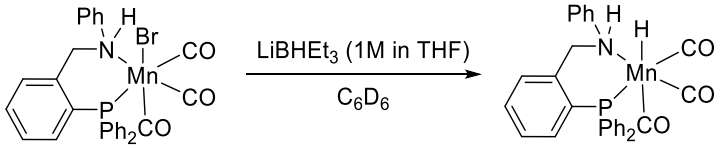
Scheme 31. The proposed pathways for the reaction of complex **24** with $LiBHEt_3$.



24 **32** **33**

Similarly, treatment of PN^HP Mn(I) complex **25** with 1.1 equivalent of $LiBHEt_3$ in C_6D_6 at room temperature showed formation of the hydride species $(PN^HP)Mn(H)(CO)_3$ (**34**; Scheme 32), characterized by an upfield Mn-H doublet at δ -6.98 ppm with $^2J_{P\text{-}H}$ = 34.6 Hz. Interestingly, the same hydride resonance was detected in ^{1}H-NMR spectra recorded directly from the reaction mixture for **25**-catalyzed TH of PhCN with NH_3BH_3 in C_6D_6, suggesting intermediacy of complex **34** in TH catalysis. Similarly to PN^HN Mn(I) hydride **32**, all attempts to fully characterize complex **34** were unsuccessful due to its decomposition *via* release of H_2 to a mixture of unknown products.

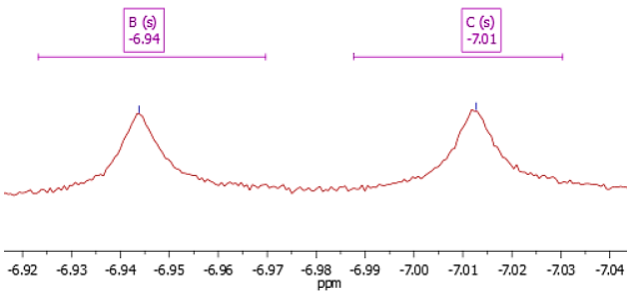
Scheme 32. Reaction of complex **25** with $LiBHEt_3$.



25 **34**

Figure 4. The hydride region of the ^{1}H-NMR spectrum taken directly from the reaction of complex **25** with $LiBHEt_3$ in C_6D_6 after 30 min at room temperature.

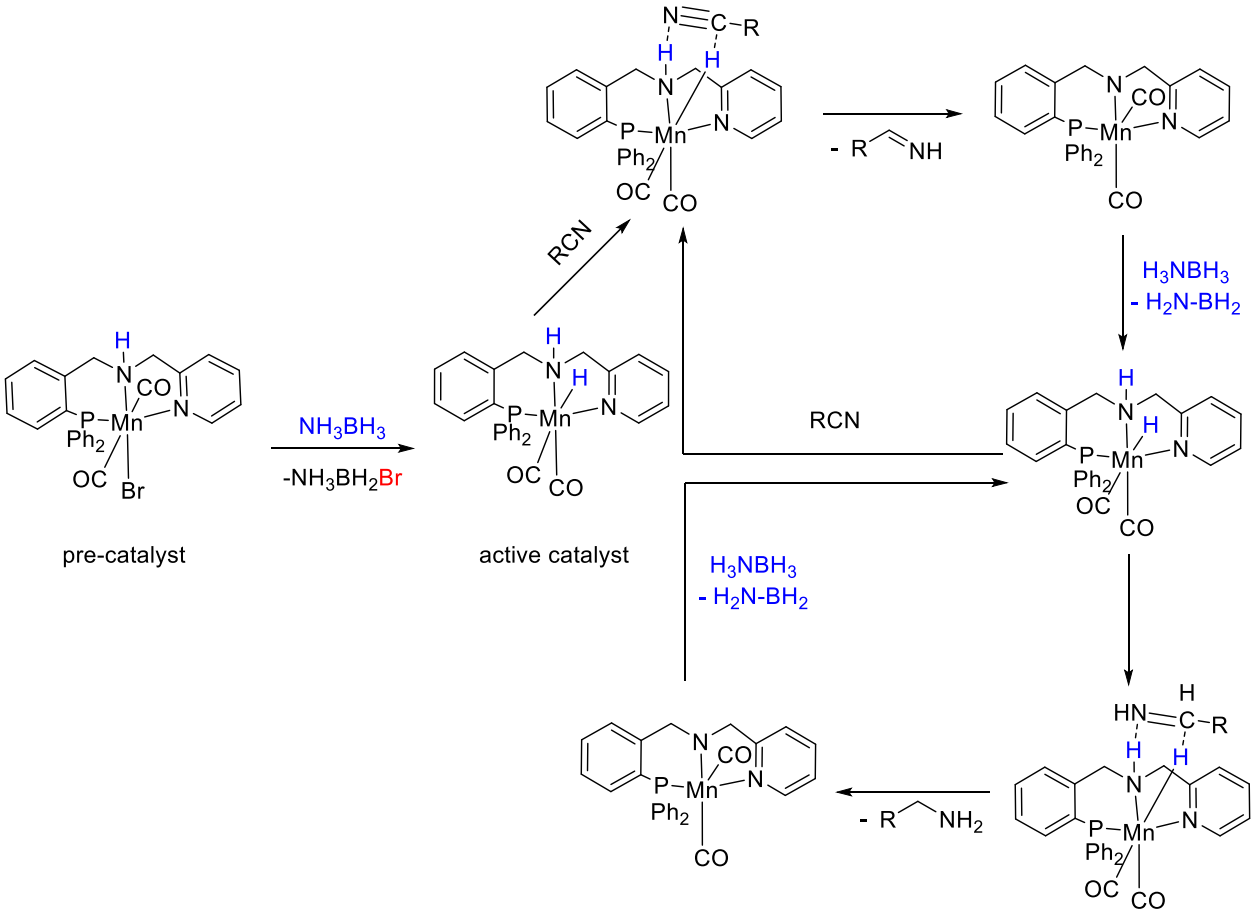
δ -6.98 (d, $^2J_{P\text{-}H}$ = 34.6 Hz, Mn*H*)



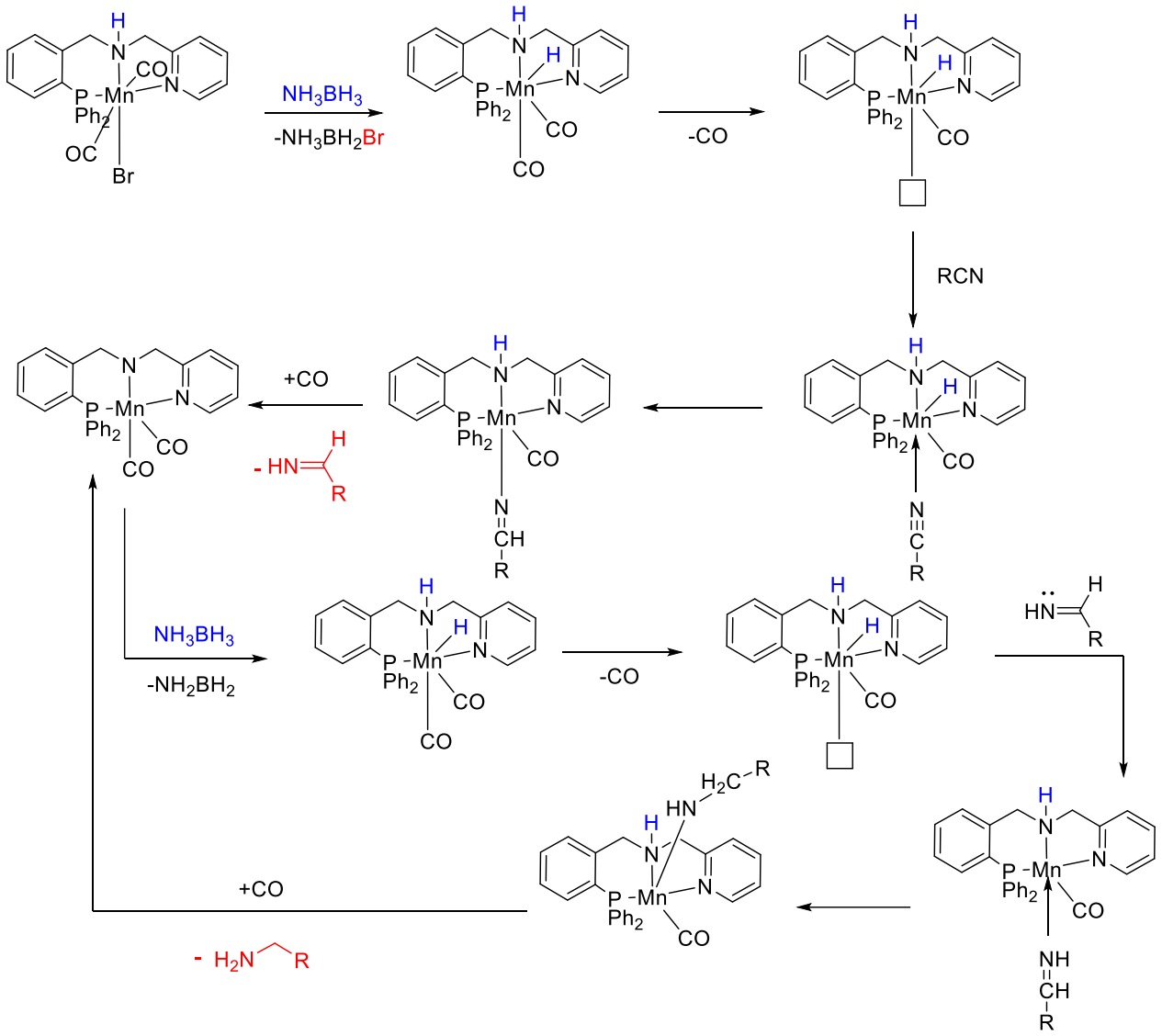
Based on this stoichiometric reactivity of complexes **24** and **25** as well as on mechanistic proposals for TH reactions catalyzed by bifunctional Mn(I) complexes, two possible mechanisms for **24**- and **25**-catalyzed TH of nitriles with ammonia borane were proposed. The first route

represents a concerted outer-sphere mechanism, in which the hydride and the proton are simultaneously transferred to the nitrile to generate a coordinatively unsaturated Mn(I) amide species and release an imine intermediate (Scheme 33; shown for $PN^{H}N$ complex **24**; the same mechanism could be also suggested for complex **25**). The catalytically active amino hydride derivative is then recovered by dehydrogenation of the ammonia borane. Reduction of the initially formed primary imine intermediate to an amine product occurs in the same manner *via* an outer-sphere mechanism. In the second inner-sphere route, after formation of the hydride species, dissociation of one CO ligand could free up the coordination site at Mn (Scheme 34; shown for $PN^{H}N$ complex **24**; the same mechanism could be also suggested for complex **25**). Subsequent coordination of the nitrile, followed by migratory insertion of the nitrile into the Mn-H bond generates the imido species, which then releases the primary imine intermediate to give the coordinatively unsaturated Mn(I) amido intermediate. This is followed by dehydrogenation of ammonia borane to recover the amino hydride catalyst. One could also argue that for complex **24**, the inner-sphere mechanism could start with the cleavage of Mn-Py fragment instead of CO dissociation. Although this pathway is possible, more detailed investigation of the plausible reaction route is necessary and will be performed in a due course.

Scheme 33. Proposed mechanism for transfer hydrogenation with NH_3BH_3 catalyzed by **24** (concerted mechanism).



Scheme 34. Proposed mechanism for transfer hydrogenation with NH_3BH_3 catalyzed by **24** (migratory insertion).



4 Materials and Methods

4.1 Materials

2-diphenylphosphinobenzaldehyde, 2-picolylamine, 2-furaldehyde, aniline, 2-methylthioaniline, dipicolylamine, $NaBH_4$, $NaBH(OAc)_3$, $NaHCO_3$, NH_3BH_3, anhydrous Na_2SO_4, HCl in diethyl ether, 1,3,5-trimethoxybenzene, $MnCl_2$, $Mn(CO)_5Br$, $Mn_2(CO)_{10}$, benzonitrile, 4-chlorobenzonitrile, 4-bromobenzonitrile, 4-methoxybenzonitrile, 4-(dimethylamino)benzonitrile, 2-thiophenecarbonitrile, cinnamonitrile, were purchased from Sigma Aldrich and used without further purification. All protonated and deuterated solvents (benzene, toluene, *n*-hexane, THF, Et_2O, CH_3CN, CD_3CN, CH_2Cl_2, CD_2Cl_2, $CDCl_3$, C_6D_6, $(CD_3)_2SO$) were dried either by distillation from suitable drying agents or using LC Technology Solutions Inc. SPBT103 benchtop solvent purification system. Methanol and 2-propanol were dried with 3Å and 4Å molecular sieves, respectively.

4.2 Equipment

All manipulations were done using standard inert atmosphere LC Technologies single station glovebox and Schlenk techniques. Schlenk glassware was used for reactions that includes substances sensitive to oxygen and/or moisture. NMR analysis was performed using JEOL ECA-500 MHz (^{1}H: 500 MHz; ^{13}C: 125.8 MHz; ^{31}P: 202.5 MHz). The ^{1}H and ^{13}C NMR chemical shifts were referenced to the residual proton and naturally abundant ^{13}C resonances of the deuterated solvents, respectively. ^{31}P spectra were referenced to 85% H_3PO_4. NMR analysis was done at room temperature under argon atmosphere using NMR tube equipped with Teflon valves (J Young NMR tubes). X-ray analysis was performed at University of Windsor by Anton Dmitrienko and using Bruker APEX-II CCD diffractometer.

4.3 Experimental Procedures

4.3.1 Preparation and characterization of N,N'-(pyridine-2,6-diylbis(methylene))bis(2,6-diisopropylaniline) (22)

The solution of lithium (2,6-diisopropylphenyl)amide (200 mg, 1.1 mmol) was added to 2,6-bis(bromomethyl)pyridine (145mg, 0.5mmol) and mixed in THF at -80ºC. After 12 h, a solution of $NaHCO_3$ (100 mL) was added to quench the reaction mixture, and the product was extracted with Et_2O. The solvent was pumped off, and the product was washed with *n*-hexane (3 times) and dried in vacuum (43.8 mg, 20 %). ^{1}H-NMR (500 MHz, C_6D_6; δ, ppm): 7.13 – 7.10 (m, 6H, ArN),

7.02-6.98 (m, 1H, Py), 6.94-6.86 (m, 2H, Py), 5.45 (br s, 2H, NH), 4.28 (s, 4H, 2 CH_2), 3.56 (sept, J = 6.8 Hz, 4H, 4 CH, ^{i}Pr), 1.24 (d, J = 6.8 Hz 24H, 8 CH_3, ^{i}Pr). The obtained NMR data are consistent with those previously published in the literature [33].

4.3.2 Preparation and characterization of N-(2-(diphenylphosphanyl)benzyl)-1-(pyridin-2-yl)methanamine pincer ligand ($PN^{H}N$)

2-picolylamine (238 mg, 2.2 mmol) was added to the solution of 2-(diphenylphosphino)benzaldehyde (580 mg, 2 mmol) in methanol at room temperature, following by the addition of Na_2SO_4 (710 mg, 5 mmol). The resulting mixture was stirred for 24 h, filtered and $NaBH_4$ (76 mg, 2 mmol) was added. The obtained mixture was gently warmed for 30 minutes at 45 ºC. The solvent was removed under reduced pressure, following by the addition of degassed water (10 mL). The organic material was extracted with Et_2O, and yellowish oil product was dried in vacuum. The compound was purified by the column chromatography on silica gel with EtOAc:NEt_3 (100:1) eluent. ^{1}H-NMR (500 MHz, $CDCl_3$; δ, ppm): 8.51-8.49 (m, 1H, *o*-H, Py), 7.57 – 7.50 (m, 2H, aromatic), 7.34 – 7.29 (m, 7H, aromatic), 7.28 – 7.24 (m, 4H, aromatic), 7.14-7.10 (m, 3H, aromatic), 6.90-6.88 (m, 1H, aromatic), 4.05 (br s, 2H, CH_2), 3.82 (s, 2H, CH_2), 2.04 (br s, 1H, NH). ^{31}P{^{1}H}-NMR (202.5 MHz, $CDCl_3$; δ, ppm): -15.3 (s, 1P, PPh_2). The obtained NMR data are consistent with those previously published in the literature [36].

4.3.3 Preparation and characterization of N-(2-(diphenylphosphanyl)benzyl)aniline ligand (PN^{H})

2-(diphenylphosphino)benzaldehyde (200 mg, 1 mmol) and aniline (67 mg, 1.1 mmol) were mixed with $NaBH(OAc)_3$ (438 mg, 3 mmol) in DCE (20 mL) under inert atmosphere at room temperature. The reaction mixture was stirred for 24 h. After that, saturated $NaHCO_3$ solution (20 mL) was added dropwise. Next, the solvent was evaporated, following by the addition of degassed water (10 mL). The product was extracted with DCM (3 times), and the DCM solution was dried with Na_2SO_4 (710 mg, 5 mmol). Finally, the solvent was pumped off, and resulting white solid product was dried in vacuum for 4 h. (100 mg, 40 %). ^{1}H-NMR (500 MHz, $CDCl_3$; δ, ppm) 7.50 – 7.47 (m, 1H, aromatic), 7.36 – 7.26 (m, 11H, aromatic), 7.18 (t, J = 7.4 Hz, 1H, aromatic), 7.10 – 7.07 (m, 2H, aromatic), 6.93 – 6.90 (m, 1H, aromatic), 6.65 (t, J = 7.3 Hz, 1H, aromatic), 6.39 (m, 2H, aromatic), 4.49 (s, 2H, CH_2), 3.93 (br s, 1H, NH). ^{31}P{^{1}H}-NMR (202.5 MHz, $CDCl_3$; δ, ppm): -15.3 (s, 1P, PPh_2). The obtained NMR data are consistent with those previously published in the literature [39].

4.3.4 Preparation and characterization of 1-(furan-2-yl)-N-(pyridin-2-ylmethyl)methanamine ligand ($ON^{H}N$)

2-furaldehyde (1g, 10mmol) and 2-picolylamine (1.2 mg, 11 mmol) were mixed in the methanol, followed by the addition of Na_2SO_4 (4.3 mg, 30 mmol). After 5h, the mixture was filtered to remove the solid particles. $NaBH_4$ (567 mg, 15 mmol) was added to the reaction mixture at 0ºC. Next, the obtained mixture was gently heated at 45ºC for 1 h. The solvent was evaporated in vacuum and the residue was extracted with DCM (3 times) and washed with brine (100 mL). Following this, the DCM fraction was separated and evaporated. The resulting dark brown residue was purified by column chromatography on silica gel with MeOH:DCM (1:10) eluent. (154 mg, 41%). ^{1}H-NMR (500 MHz, $CDCl_3$; δ, ppm): 7.63 – 7.66 (m, 1H), 7.55 – 7.56 (m, 1H), 7.36 (m, 1H), 7.31 (d, J = 7.8 Hz, 1H), 7.16 – 7.18 (m, 1H), 6.30 – 6.31 (m, 1H), 6.23 (m, 1H), 3.95 (s, 2H, CH_2), 3.87 (s, 2H, CH_2), 2.71 (br s, 1H, NH). The obtained NMR data are consistent with those previously published in the literature [25].

4.3.5 Preparation and characterization of 1-(2-(diphenylphosphanyl)phenyl)-N-(2-(methylthio)phenyl)methanimine ($PN^{imine}S$) ligand

The 2-diphenylphosphinobenzaldehyde (150 mg, 1 mmol) and 2-methylthioaniline (79 mg, 1.1 mmol) were mixed in toluene and stirred under reflux for 4 days. The reaction mixture was cooled down to room temperature, and the solvent was evaporated. The obtained yellow residue was washed with *n*-hexane (3 times) and dried in vacuum. (80 mg, 35 %). ^{1}H-NMR (500 MHz, $CDCl_3$; δ, ppm): 8.38 (m, 1H, -CH=N-), 7.46 (m, 1H, aromatic), 7.38 – 7.29 (m, 12H, aromatic), 7.15 (d, J = 4.1 Hz, 2H, aromatic), 7.05 – 7.00 (m, 1H), 6.91 (m, 1H, CH), 6.92 (m, 1H, aromatic), 2.31 (s, 3H, CH_3).

4.3.6 Preparation and characterization of manganese complexes

$(DPA)_2Mn(CO)_4$ (21)

Dipicolylamine (40 mg, 0.2 mmol) was mixed with $Mn_2(CO)_{10}$ (40 mg, 0.1 mmol) in toluene. The reaction mixture was heated in the oil bath at 80 ºC and stirred for 2 days. Yellow precipitate of the product formed. The solvent was pumped off and the residue was dried in vacuum. (494 mg, 45 %.) ^{1}H-NMR (500 MHz, CD_3CN, δ, ppm): 8.90 (s, 4H, Py), 7.74 (br s, 4H, Py), 7.58 (s, 4H, 2CH of Py), 7.35 (m, 4H, 2CH of Py), 6.11 (s, 2H, NH), 4.74 (s, 4H, 2 CH_2). $^{13}C\{^1H\}$-NMR (125.8 MHz; $(CD_3)_2SO$; δ, ppm): 161.51 (s), 140.05 (s), 126.10(s), 125.87 (s), 123.53 (s), 118.31 (s), 62.3 (s).

[($N^{H}NN^{H}$)$Mn(CO)_3$]Br (23)

N,N'-(pyridine-2,6-diylbis(methylene))bis(2,6-diisopropylaniline) ligand (27 mg, 0.06 mmol) and $Mn_2(CO)_{10}$ (12 mg, 0.03 mmol) were mixed in C_6D_6 at room temperature. The resulting mixture was heated in the oil bath at 80 ºC for 72 h. After that, the solvent was evaporated in vacuum, and the residue was dried in vacuum for 5 h. ^{1}H-NMR (500 MHz, $(CD_3)_2SO$, δ, ppm): 7.75 (br s, 1H, aromatic), 7.35 (br s, 2H, aromatic), 7.21 (br s, 1H, aromatic), 7.10-7.14 (br m, 1H, aromatic), 7.02 (br s, 2H, aromatic), 6.96 (br s, 2H, aromatic), 4.40 (br s, 2H, 2NH), 4.07 (s, 4H, $2CH_2$), 3.34 (br s, 4H, 4CH, ^{i}Pr), 1.11 (br s, 24H, $8CH_3$, ^{i}Pr).

($PN^{H}N$)$MnBr(CO)_2$ (24)

N-(2-(diphenylphosphanyl)benzyl)-1-(pyridin-2-yl)methanamine (124 mg, 0.31 mmol) ligand was added to the suspension of $Mn(CO)_5Br$ (86mg, 0.31mmol) in THF. The reaction mixture was stirred for 16 h at 80 ºC. The solvent was pumped off; the residue was washed with *n*-hexane (3 times) and dried in vacuum. (115 mg, 64 %). ^{1}H-NMR (500 MHz, CD_2Cl_2; δ, ppm): 9.06-9.13 (br s, 1H, aromatic); 8.07 (br s, 1H, aromatic), 7.67 (br s, 1H, aromatic); 7.25-7.54 (m, 12H, aromatic); 7.05 (t, *J* = 8.4 Hz, 2H, aromatic); 6.81 (t, *J* = 8.1 Hz, 1H, aromatic), 4.57- 4.16 (m, 4H, $2CH_2$), 3.95 (br s, 1H, NH). ^{31}P-NMR (202.5 MHz, CD_2Cl_2; δ, ppm): 72.2 (s, 1P, PPh_2). The obtained NMR data are consistent with those previously published in the literature [34,35].

(PN^{H})$MnBr(CO)_3$ (25)

N-(2-(diphenylphosphanyl)benzyl)aniline ligand (50 mg, 0.13 mmol) and $Mn(CO)_5Br$ (37 mg, 0.13 mmol) were mixed in the toluene and heated at 80 ºC for 24 h. The solvent was pumped off, and the residue was dried in vacuum (51 mg, 64%). ^{1}H-NMR (500 MHz, C_6D_6; δ, ppm): 7.98 (br s, 2H, aromatic), 7.58-7.41 (m, 8H, aromatic), 7.40-7.33 (m, 3H, aromatic), 7.32 – 7.24 (m, 2H, aromatic), 7.22 – 7.14 (m, 3H, aromatic), 6.91 (t, *J* = 8.4 Hz, 1H, aromatic), 4.75 (d, *J* = 9.6 Hz, 1H), 4.49 (t, *J* = 10.9 Hz, 1H), 4.12 (dd, *J* = 11.8, 3.3 Hz, 1H). ^{31}P-NMR (202.5 MHz, $CDCl_3$; δ, ppm): 37.9 (s, 1P, PPh_2). $^{13}C\{^1H\}$-NMR (125.8 MHz; C_6D_6; δ, ppm): 158.8 (s), 154.0 (s), 151.6 (s), 139.1 (s), 138.6 (s), 136.4 (s), 134.0 (s), 133.5 (s) 128.9 (s), 128.7 (s), 128.1 (s), 125.9 (s), 120.9 (s), 60.0 (s).

($PN^{imine}S$)$MnBr(CO)_2$ (26)

1-(2-(diphenylphosphanyl)phenyl)-N-(2-(methylthio)phenyl)methanimine (15 mg, 0.04 mmol) and $Mn(CO)_5Br$ (10 mg, 0.04 mmol) were mixed in dry THF in the presence of $(CH_3)_3NO$ (8 mg, 0.1 mmol). The reaction mixture was stirred at room temperature overnight, and the product was analyzed by NMR without its isolation. ^{31}P-NMR (202.5 MHz, $CDCl_3$; δ, ppm): 77.1 (s,1P, PPh_3).

($ON^{H}N$)$MnCl_2$ (28)

1-(furan-2-yl)-N-(pyridin-2-ylmethyl)methanamine (154 mg, 0.8 mmol) ligand was added to the suspension of $MnCl_2$ (102.8 mg, 0.8 mmol) in THF. The resulting mixture was stirred at room temperature for 24 h. After that, the light brown precipitate was formed. The solvent was pumped off, and the residue was dried in the vacuum for 24 h. (186.55 mg, 37%). The obtained complex is paramagnetic and air stable. For further characterization by X-ray diffraction analysis, the complex **28** was crystallized from DCM at 8ºC.

General procedure for transfer hydrogenation of nitriles

NH_3BH_3 (0.3mmol), a nitrile substrate (0.1 mmol) and a catalyst (**24**, **25**, **28** depending on experiment) (5 mol %) were placed into a Sulpeco® pressure vial, equipped with a magnetic stirrer. 1.5 mL of either C_6D_6 or 2-propanol (depending on experiment) were added. The vial was sealed and placed in an oil bath 80ºC for 24 h with intensive stirring. After that, an excess of methanol was added, and the mixture was stirred for 1 h. Following this, MeOH was evaporated, and the excess of HCl in Et_2O or dioxane resulting in precipitation of the corresponding ammonium salt. The obtained precipitate was washed with cold Et_2O (5 times) and dried in vacuum for 12 h. The products were characterized by NMR spectroscopy using either D_2O, $(CD_3)_2SO$ or $CDCl_3$ solvents.

NMR data for isolated ammonium salts and generated secondary imine products:

Benzylamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.42 (s, 5H, aromatic), 4.12 (s, 2H, CH_2). The obtained NMR data are consistent with those previously published in the literature [25].

4-methoxybenzylamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.27 (d, *J* = 8.1 Hz, 2H, CH), 6.90 (d, *J* = 8.3 Hz, 1H, CH), 3.99 (s, 2H, CH_2), 3.71 (s, 3H, CH_3). The obtained NMR data are consistent with those previously published in the literature [25].

4-brombenzylamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.44 (d, *J* = 7.2 Hz, 2H, CH), 7.25 (d, *J* = 7.1 Hz, 2H, CH), 4.10 (s, 2H, CH_2). The obtained NMR data are consistent with those previously published in the literature [25].

4-chlorobenzylamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.39 (d, *J* = 8.0 Hz, 2H, CH), 7.33 (d, *J* = 8.0 Hz, 2H, CH), 4.05 (s, 2H, CH_2). The obtained NMR data are consistent with those previously published in the literature [25].

4-dimethylaminobenzylamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.56 (d, *J* = 6.5 Hz, 4H, CH), 7.38 (d, *J* = 6.5 Hz, 2H, CH), 4.15 (s, 2H, CH_2), 3.19 (s, 6H, $2CH_3$). $^{13}C\{^1H\}$-NMR (125.8 MHz; D_2O; δ, ppm): 144.33 (s), 132.59 (s), 130.82 (s), 120.08 (s), 45.22 (s), 42.28 (s).

Thiophen-2-ylmethanamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.42 (t, J = 8.5 Hz, 1H, CH), 7.15 (br s, 1H, CH), 7.03 (br s, 1H, CH), 4.31 (s, 2H, CH_2). $^{13}C\{^{1}H\}$-NMR (125.8 MHz; D_2O; δ, ppm): 133.75 (s), 129.52 (s), 127.96 (s), 127.73 (s), 37.36 (s).

Methyl 4-aminobenzoate hydrochloride: ^{1}H-NMR (500 MHz, $(CD_3)_2SO$; δ, ppm): 7.91 (br s, 2H, 2CH of Ar), 7.28 (br s, 2H, 2CH of Ar), 4.47 (s, 2H, CH_2), 3.79 (s, 3H, CH_3). $^{13}C\{^{1}H\}$-NMR (125.8 MHz; $(CD_3)_2SO$; δ, ppm): 166.72 (s), 142.03 (s), 129.61 (s), 126.93 (s), 63.18 (s), 52.57 (s), 40.25 (s).

Phenylpropylamine hydrochloride: ^{1}H-NMR (500 MHz, D_2O; δ, ppm): 7.43 (m, 2H), 7.31 (m, 3H), 2.83 (m, 2H), 2.60 (m, 2H), 2.53 (m, 2H).

N-Benzylbenzaldimine: ^{1}H-NMR (500 MHz, $CDCl_3$, δ, ppm) 8.32 (s, 1H, NH), 7.70 (br s, 2H, CH), 7.33-7.17 (m, 8H, CH), 4.75 (s, 2H, CH_2). The obtained NMR data are consistent with those previously published in the literature [40].

N-(4-chlorobenzyl)-1-(4-chlorophenyl)methanimine: ^{1}H-NMR (500 MHz, $CDCl_3$, δ, ppm): 8.30 (s, 1H, NH), 7.68 -7.39 (m, 8H, aromatic), 4.77 (s, 2H, CH_2). The obtained NMR data are consistent with those previously published in the literature [40].

Crystallographic parameters for $PN^{H}MnBr(CO)_3$

Bond precision: C-C = 0.0064 A Wavelength=0.71073

Cell: a=7.8473(5) b=11.8074(8) c=16.0165(11)
alpha=75.388(2) beta=84.544(2) gamma=84.814(2)

Temperature: 170 K

	Calculated	Reported
Volume	1426.12(17)	1426.12(17)
Space group	P -1	P -1
Hall group	-P 1	-P 1
Moiety formula	C28 H22 Br Mn N O3 P [+ solvent]	C28 H22 Br Mn N O3 P
Sum formula	C28 H22 Br Mn N O3 P [+ solvent]	C28 H22 Br Mn N O3 P
Mr	586.28	586.28
Dx,g cm-3	1.365	1.365
Z	2	2
Mu (mm-1)	1.947	1.947
F000	592.0	592.0
F000'	592.50	
h,k,lmax	10,15,21	10,15,21
Nref	7173	7140
Tmin,Tmax	0.795,0.876	0.665,0.746
Tmin'	0.776	

Correction method= # Reported T Limits: Tmin=0.665 Tmax=0.746 AbsCorr = MULTI-SCAN

Data completeness= 0.995 Theta(max)= 28.380

R(reflections)= 0.0556(5463) wR2(reflections)= 0.1595(7140)

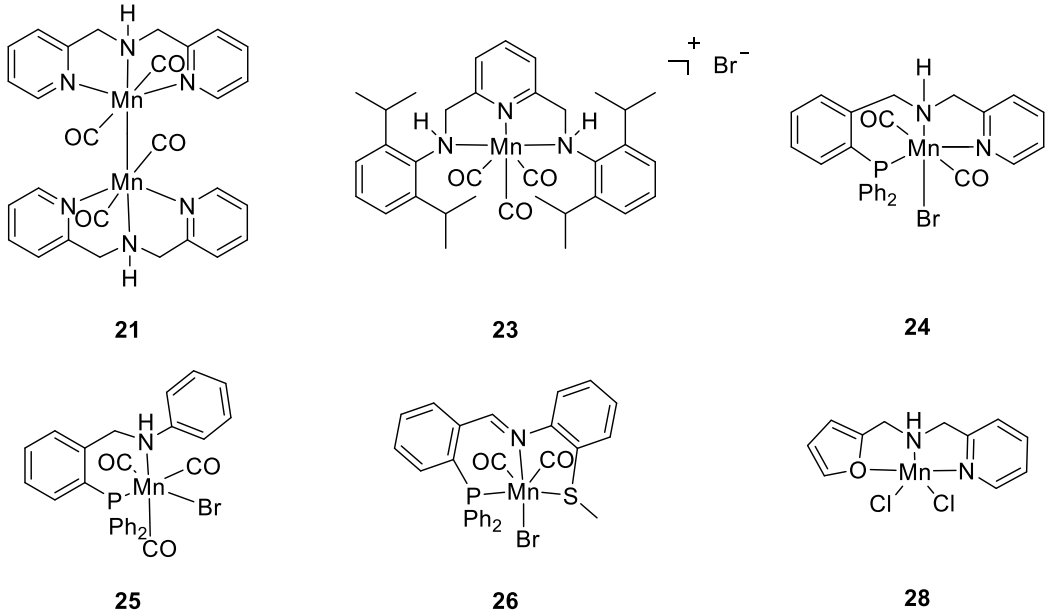
S = 1.044 Npar= 316

5 Conclusion and Future Perspectives

To sum up, this thesis describes the synthesis and evaluation of catalytic transfer hydrogenation activity of manganese complexes with polydentate bifunctional ligands bearing secondary amine functionality. A series of novel Mn(0), Mn(I) and Mn(II) complexes were prepared and characterized. Mn(I) and Mn(II) complexes, $[(N^{H}NN^{H})Mn(CO)_3]Br$ (**23**), $(PN^{H}N)MnBr(CO)_2$ (**24**), $(PN^{H})MnBr(CO)_3$ (**25**) and $(NN^{H}O)MnCl_2$ (**28**), were tested in catalytic transfer hydrogenation of nitriles with ammonia borane as the hydrogen source. Selective reduction of nitriles to primary amines was demonstrated in benzene, with the highest catalytic activity observed for Mn(I) derivatives **24** and **25**. The Mn(II) complex **28** was also found to mediate reduction of nitriles to primary amines, demonstrating a rare example of Mn(II) pre-catlyst for transfer hydrogenation reactions. Moreover, the selectivity of TH reactions was found to be highly sensitive to the choice of solvent, and instead of primary amine products produced in benzene, the reactions in 2-propanol showed formation of secondary imine products.

The study of the stoichiometric reactivity of complexes **24** and **25** with $LiBHEt_3$ suggested formation of the hydride species as active TH catalysts. Based on this and the observations of the same hydride species during catalytic TH of PhCN, a metal-ligand cooperative mechanism for transfer hydrogenations was proposed. However, further mechanistic studies and control experiments are necessary to differentiate between inner- and outer-sphere pathways.

Figure 5. Prepared manganese complexes.



Despite successful achievements of the thesis objectives, further work is necessary to elucidate the following aspects of the prepared manganese pre-catalysts and catalytic TH reactions:

1. Considering the paramagnetic nature of complex **28**, a single crystal X-ray diffraction analysis of this compound would be helpful to further support its structure.
2. The scope of catalytic TH reactions has to be expanded for better assessment of applicability of the developed systems to different classes of nitrile substrates and to study the selectivity of these transformations.
3. Additional studies have to be performed to better understand the selectivity of catalytic TH reactions in different solvents.
4. More detailed study of the mechanism of Mn-catalyzed TH reactions is necessary to optimize the catalyst structure and the reaction conditions. This includes kinetic NMR studies of catalytic reactions and a series of control experiments, allowing to differentiate between inner- *vs.* outer-sphere mechanisms and assess the potential hemilabile behavior of $PN^{H}N$, PNS and $NN^{H}O$ ligands. The crucial role of the secondary amine functionality can be also assessed though comparative catalytic tests with analogous complexes, not having NH functionality in the ligand backbone, akin to $(PN^{R}N)MnBr(CO)_2$, $(PN^{R})MnBr(CO)_3$ and $(NN^{R}O)MnCl_2$ (where R = Me, for example).

References

1. Clapham, S. E.; Hadzovic, A.; Morris, R. H. Mechanisms of the H2-Hydrogenation and Transfer Hydrogenation of Polar Bonds Catalyzed by Ruthenium Hydride Complexes. *Coord. Chem. Rev.* **2004**, *248* (21–24), 2201–2237.
2. Gomez, S.; Peters, J. A.; Maschmeyer, T. The Reductive Amination of Aldehydes and Ketones and the Hydrogenation of Nitriles: Mechanistic Aspects and Selectivity Control. *Adv. Synth. Catal.* **2002**, *344* (10), 1037–1057.
3. Blaser, H.-U.; Malan, C.; Pugin, B.; Spindler, F.; Steiner, H.; Studer, M. Selective Hydrogenation for Fine Chemicals: Recent Trends and New Developments. *Adv. Synth. Catal.* **2003**, *345* (12), 103–151.
4. Werkmeister, S.; Junge, K.; Beller, M. Catalytic Hydrogenation of Carboxylic Acid Esters, Amides, and Nitriles with Homogeneous Catalysts. *Org. Process Res. Dev.* **2014**, *18* (2), 289–302.
5. Bagal, D. B.; Bhanage, B. M. Recent Advances in Transition Metal-Catalyzed Hydrogenation of Nitriles. *Adv. Synth. Catal.* **2015**, *357* (5), 883–900.
6. Roose, P.; Eller, K.; Henkes, E.; Rossbacher, R.; Höke, H. Amines, Aliphatic. *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley: Weinheim, 2015, pp 1–55.
7. Heuer, L. Benzylamine. *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH, Ed.; Wiley-VCH Verlag: Weinheim, Germany, 2002.
8. Wang, D.; Astruc, D. The Golden Age of Transfer Hydrogenation. *Chem. Rev.* **2015**, *115* (13), 6621–6686.
9. Baidilov, D.; Hayrapetyan, D.; Khalimon, A. Y. Recent Advances in Homogeneous Base-Metal-Catalyzed Transfer Hydrogenation Reactions. *Tetrahedron* **2021**, *98*, 132435.
10. Lévay, K.; Hegedűs, L. Recent Achievements in the Hydrogenation of Nitriles Catalyzed by Transitional Metals. *Curr. Org. Chem.* **2019**, *23* (18), 1881–1900.
11. Alig, L.; Fritz, M.; Schneider, S. First-Row Transition Metal (DE)Hydrogenation Catalysis Based on Functional Pincer Ligands. *Chem. Rev.* **2019**, *119* (4), 2681–2751.
12. Sklyaruk, J.; Zubar, V.; Borghs, J. C.; Rueping, M. Methanol as the Hydrogen Source in the Selective Transfer Hydrogenation of Alkynes Enabled by a Manganese Pincer Complex. *Org. Lett.* **2020**, *22* (15), 6067–6071.
13. Garduño, J. A.; García, J. J. Nickel-Catalyzed Transfer Hydrogenation of Benzonitriles with 2-Propanol and 1,4-Butanediol as the Hydrogen Source. *ACS Omega* **2017**, *2* (5), 2337–2343.
14. Oates, C. L.; Widegren, M. B.; Clarke, M. L. Manganese-Catalysed Transfer Hydrogenation of Esters. *Chem. Commun.* **2020**, *56* (61), 8635–8638.

15. Shao, Z.; Fu, S.; Wei, M.; Zhou, S.; Liu, Q. Mild and Selective Cobalt-catalyzed Chemodivergent Transfer Hydrogenation of Nitriles. *Angew. Chem. Int. Ed.* **2016**, *55* (47), 14653–14657.
16. Segizbayev, M.; Öztopçu, Ö.; Hayrapetyan, D.; Shakhman, D.; Lyssenko, K. A.; Khalimon, A. Y. Transfer Hydrogenation of Aldehydes and Ketones Catalyzed Using an Aminophosphinite POCNH Pincer Complex of Ni(Ii). *Dalton Trans.* **2020**, *49* (34), 11950–11957.
17. Gudun, K. A.; Slamova, A.; Hayrapetyan, D.; Khalimon, A. Y. Efficient Co-Catalyzed Double Hydroboration of Nitriles: Application to One-Pot Conversion of Nitriles to Aldimines. *Chem. Eur. J.* **2020**, *26* (22), 4963–4968.
18. Gudun, K. A.; Zakarina, R.; Segizbayev, M.; Hayrapetyan, D.; Slamova, A.; Khalimon, A. Y. Cobalt-catalyzed Deoxygenative Hydroboration of Nitro Compounds and Applications to One-pot Synthesis of Aldimines and Amides. *Adv. Synth. Catal.* **2022**, *364* (3), 601–611.
19. Adilkhanova, A.; Frolova, V. F.; Yessengazin, A.; Öztopçu, Ö.; Gudun, K. A.; Segizbayev, M.; Matsokin, N. A.; Dmitrienko, A.; Pilkington, M.; Khalimon, A. Y. Synthesis and Catalytic Performance of Nickel Phosphinite Pincer Complexes in Deoxygenative Hydroboration of Amides. *Dalton Trans.* **2023**, *52* (9), 2872–2886.
20. Khalimon, A.; Gudun, K.; Hayrapetyan, D. Base Metal Catalysts for Deoxygenative Reduction of Amides to Amines. *Catalysts* **2019**, *9* (6), 490.
21. Gudun, K. A.; Tussupbayev, S.; Slamova, A.; Khalimon, A. Y. Hydroboration of Isocyanates: Cobalt-Catalyzed vs. Catalyst-Free Approaches. *Org. Biomol. Chem.* **2022**, *20* (34), 6821–6830.
22. Perez, M.; Elangovan, S.; Spannenberg, A.; Junge, K.; Beller, M. Molecularly Defined Manganese Pincer Complexes for Selective Transfer Hydrogenation of Ketones. *ChemSusChem* **2017**, *10* (1), 83–86.
23. Martínez-Ferraté, O.; Werlé, C.; Franciò, G.; Leitner, W. Aminotriazole Mn(I) Complexes as Effective Catalysts for Transfer Hydrogenation of Ketones. *ChemCatChem* **2018**, *10* (20), 4514–4518.
24. Garduño, J. A.; Flores-Alamo, M.; García, J. J. Manganese-catalyzed Transfer Hydrogenation of Nitriles with 2-butanol as the Hydrogen Source. *ChemCatChem* **2019**, *11* (21), 5330–5338.
25. Sarkar, K.; Das, K.; Kundu, A.; Adhikari, D.; Maji, B. Phosphine-Free Manganese Catalyst Enables Selective Transfer Hydrogenation of Nitriles to Primary and Secondary Amines Using Ammonia–Borane. *ACS Catal.* **2021**, *11* (5), 2786–2794.

26. Werkmeister, S.; Bornschein, C.; Junge, K.; Beller, M. Selective Ruthenium-Catalyzed Transfer Hydrogenations of Nitriles to Amines with 2-Butanol. *Chem. Eur. J.* **2013**,*19* (14), 4437–4440.
27. Werkmeister, S.; Bornschein, C.; Junge, K.; Beller, M. Ruthenium-Catalyzed Transfer Hydrogenation of Nitriles: Reduction and SubsequentN-Monoalkylation to Secondary Amines: Ruthenium-Catalyzed Transfer Hydrogenation of Nitriles. *Eur. J. Org. Chem.* **2013**, *2013* (18), 3671–3674.
28. Lee, S.-H.; Nikonov, G. I. Transfer Hydrogenation of Ketones, Nitriles, and Esters Catalyzed by a Half-Sandwich Complex of Ruthenium. *ChemCatChem* **2015**, *7* (1), 107–113.
29. Gutsulyak, D. V.; Nikonov, G. I. Chemoselective Catalytic Hydrosilylation of Nitriles. *Angew. Chem. Int. Ed.* **2010**, *49* (41), 7553–7556.
30. Mai, V. H.; Nikonov, G. I. Transfer Hydrogenation of Nitriles, Olefins, and N-Heterocycles Catalyzed by an N-Heterocyclic Carbene-Supported Half-Sandwich Complex of Ruthenium. *Organometallics* **2016**, *35* (7), 943–949.
31. Alshakova, I. D.; Gabidullin, B.; Nikonov, G. I. Ru-catalyzed Transfer Hydrogenation of Nitriles, Aromatics, Olefins, Alkynes and Esters. *ChemCatChem* **2018**, *10* (21), 4860–4869.
32. Grotjahn, D. B.; Van, S.; Combs, D.; Lev, D. A.; Schneider, C.; Incarvito, C. D.; Lam, K.-C.; Rossi, G.; Rheingold, A. L.; Rideout, M.; Meyer, C.; Hernandez, G.; Mejorado, L. Substituent Control of Hydrogen Bonding in Palladium(II)-Pyrazole Complexes. *Inorg. Chem.* **2003**, *42* (10), 3347–3355.
33. Guérin, F.; McConville, D. H.; Vittal, J. J. Conformationally Rigid Diamide Complexes of Zirconium: Electron Deficient Analogues of Cp_2Zr. *Organometallics* **1996**, *15* (26), 5586–5590.
34. Zubar, V.; Lichtenberger, N.; Schelwies, M.; Oeser, T.; Hashmi, A. S. K.; Schaub, T. Manganese-catalyzed Hydrogenation of Sclareolide to Ambradiol. *ChemCatChem* **2022**, *14* (1), 1-5.
35. Li, X.-G.; Li, F.; Xu, Y.; Xiao, L.-J.; Xie, J.-H.; Zhou, Q.-L. Hydrogenation of Esters by Manganese Catalysts. *Adv. Synth. Catal.* **2022**, *364* (4), 744–749.
36. Del Zotto, A., Baratta, W., Ballico, M., Herdtweck, E. and Rigo, P. [$RuCl_2(PPh_3)$(PNN‘)] Complexes as Efficient Catalysts in Transfer Hydrogenation of Ketones. *Organometallics* **2007,** *26* (23), 5636-5642.
37. Cotton, F. A. *Advanced Inorganic Chemistry: A Comprehensive Text*, 3rd ed.; Interscience, 1972.
38. Fulmer, G. R.; Miller, A. J. M.; Sherden, N. H.; Gottlieb, H. E.; Nudelman, A.; Stoltz, B. M.; Bercaw, J. E.; Goldberg, K. I. NMR Chemical Shifts of Trace Impurities: Common Laboratory

Solvents, Organics, and Gases in Deuterated Solvents Relevant to the Organometallic Chemist. *Organometallics* **2010**, *29* (9), 2176–2179.

39. Traut-Johnstone, T.; Kanyanda, S.; Kriel, F. H.; Viljoen, T.; Kotze, P. D. R.; van Zyl, W. E.; Coates, J.; Rees, D. J. G.; Meyer, M.; Hewer, R.; Williams, D. B. G. Heteroditopic P,N Ligands in Gold(I) Complexes: Synthesis, Structure and Cytotoxicity. *J. Inorg. Biochem.* **2015**, *145*, 108–120.
40. Chu, G.; Li, C. Convenient and Clean Synthesis of Imines from Primary Benzylamines. *Org. Biomol. Chem.* **2010**, *8* (20), 4716–4719.