Universität Rostock Traditio et Innovatio

Katalysis LIKAT Leibniz-Institut für Katalyse e.V.

Iron- and Manganese-Catalysed (De)Hydrogenation Reactions

Cumulative Dissertation

to acquire the academic degree
doctor rerum naturalium (Dr. rer. nat.)
of the Faculty of Mathematics and Natural Sciences
at the University of Rostock

Submitted by Svenja Budweg, born on 8th January 1990 in Ravensburg

Rostock, 09.03.21

https://doi.org/10.18453/rosdok_id00003151

The present work was accomplished at the Leibniz-Institute for Catalysis e.V. at the University of Rostock, at the chair for Applied Catalysis in the work group of Professor Dr. Matthias Beller during the period from April 2018 to March 2021. The defense took place on the 29th June 2021.

Reviewer #1: Prof. Dr. Matthias Beller
Leibniz-Institut für Katalyse e.V.
Angewandte Homogenkatalyse
Albert-Einstein-Straße 29a
18059 Rostock

Reviewer #2: Prof. Dr. Christophe Darcel
263 Av. Général Leclerc,
35700 Rennes, France

Statement of Authorship

I hereby affirm that I have written the present work by myself without outside assistance. No other resources were utilised than stated. All references as well as verbatim extracts were quoted, and all sources of information were specifically acknowledged.

Ich versichere hiermit an Eides statt, dass ich die vorliegende Arbeit selbstständig angefertigt und ohne fremde Hilfe verfasst habe. Dazu habe ich keine außer den von mir angegebenen Hilfsmitteln und Quellen verwendet. Die den benutzten Werken inhaltlich und wörtlich entnommenen Stellen habe ich als solche kenntlich gemacht.

Rostock, 09.03.2021

…….
Svenja Budweg

Acknowledgements - Danksagung

Eine Doktorarbeit ist nie das Werk eines Einzelnen. Ich möchte mich deshalb bei einigen wichtigen Personen bedanken, die einen Beitrag zu der vorliegenden Arbeit geleistet haben.

An erster Stelle möchte ich Herrn **Prof. Dr. Matthias Beller** für die Aufnahme in seinen Arbeitskreis und die Vergabe des sehr interessanten Themas bedanken. Die wissenschaftlichen Diskussionen und die neuen Ideen zu meiner Forschung haben maßgeblich zum Gelingen dieser Arbeit beigetragen. Die Unterstützung, um ein Praktikum bei der Bayer AG zu bekommen hat mir zu wertvollen Erfahrungen verholfen und auch die Möglichkeit an einem Industrieprojekt während meiner Promotionsphase zu arbeiten war für mich eine Bereicherung.

Bei **Dr. Kathrin Junge** möchte ich mich für die Aufnahme in die Redox-Gruppe und den bereitgestellten Arbeitsplatz bedanken. Ich bin dankbar für die angenehme Arbeitsatmosphäre und deine stetige Unterstützung im beruflichen als auch privaten Bereich.

Der gesamten **Redox-Gruppe** möchte ich für das angenehme Arbeitsklima und die schöne gemeinsame Zeit danken.
Den ehemaligen Mitgliedern **Dr. Marcel Garbe**, **Dr. Jacob Schneekönig** und **Bianca Tannert** danke ich für die gemeinsame Zeit, die vielen hilfreichen Tipps und Tricks und die lustigen „Nebenprojekte“. Zahlreiche Anekdoten werden mir immer in guter Erinnerung bleiben.
In particular, I want to thank **Dr. Wu Li** and **Florian Bourriquen** for our great time together in the lab. It was a pleasure to work with you both and I really enjoyed the good working atmosphere. Thanks for introducing me into the “carbonblack”-side of heterogeneous chemistry and your help whenever I needed it.
Bei **Helen Hornke** bedanke ich mich für ihre herzliche und offene Art und dass sie den gewissen Pepp in unser Labor gebracht hat. Ich wünsche dir noch viele Forschungsprojekte, an denen du Spaß findest und weiterwächst.
Bei **Dr. Thomas Leischner** möchte ich mich für die zahlreichen neuen Ideen und guten Ratschläge zu meiner Forschung bedanken.
Den aktuellen Mitgliedern **Dr. Peter McNeice**, **Johannes Fessler**, **Shuxin Mao**, **David Leonard** und **Niklas Heinrich** danke ich für die gemeinsame Zeit und die stetige Hilfsbereitschaft.

Der analytischen Abteilung, und besonders **Dr. Christine Fischer**, **Susanne Schareina**, **Susann Buchholz** und **Katrin Fiedler**, möchte ich für die Vermessung zahlreicher NMR-Spektren und GC-Proben danken. **Dr. Anke Spannenberg** danke ich für die gemessenen X-Ray Strukturen und deren Auswertung.

Des Weiteren danke ich meiner **Familie** und im Besonderen meinem Vater und meiner Oma Liese. Durch das Vertrauen in mich und eure stetige Unterstützung (gerade im letzten Jahr) habt ihr diese Arbeit möglich gemacht. Ich danke auch meinen **Freunden**, die in der gesamten Zeit meines Studiums und auch in schwierigen Situationen an meiner Seite waren.

Meinem Mann **Max**, danke ich für die beständige Unterstützung in den letzen Jahren. Du hast einen großen Teil zu dieser Arbeit beigetragen, indem du immer für mich da warst und mich immer in meinen Entscheidungen bekräftigt hast. Deine Zuversicht und dein Verständnis haben mir nach Sophie neuen Mut gegeben. Ich freue mich auf unsere weitere gemeinsame Zeit.

Summary

This work relates to the development of new methodologies for homogeneously catalysed (de)hydrogenation reactions. The focus is on non-noble metal catalysts based on iron or manganese with varying pincer ligands for the dehydrogenation of alcohols and the semihydrogenation of alkynes. In a first protocol, the transfer dehydrogenation of secondary alcohols was demonstrated, which proceeds by means of an iron PNP pincer complex as catalyst, and acetone as hydrogen acceptor. The ensuing publication showed the same dehydrogenation reaction. However, the focus was on a manganese-based *in situ* system, consisting of $MnBr(CO)_5$ and a phosphorus-free NNN pincer ligand. Subsequently, the semihydrogenation of alkynes with a manganese PNP-pincer complex and molecular hydrogen was presented. The hydrogenation proceeded stereoselectively, exclusively the corresponding *Z*-alkenes were formed.

Zusammenfassung

Die vorliegende Arbeit beschreibt die Entwicklung von neuen Methoden für homogenkatalytische (De)Hydrierungsreaktionen. Dabei wurden Nichtedelmetallkatalysatoren auf Basis von Eisen oder Mangan mit variierenden Pincer-Liganden für die Dehydrierung von Alkoholen und die Semihydrierung von Alkinen eingesetzt. In ersten Arbeiten wurde die Transfer-Dehydrierung von sekundären Alkoholen gezeigt, die mittels eines Eisen PNP-Pincerkomplex und Aceton als Wasserstoffakzeptor stattfindet. Die darauffolgenden Arbeiten nutzten die gleiche Reaktion, allerdings war hier der Fokus auf einem mangan-basierten *in situ* System, welches aus $MnBr(CO)_5$ und einem phosphorfreiem NNN-Pincerligand gebildet wird. Anschließend wurde die Semihydrierung von Alkinen mittels eines Mangan PNP-Pincerkomplexes und unter Verwendung von molekularem Wasserstoff realisiert. Die Hydrierung verläuft stereoselektiv und es wurden ausschließlich die zugehörigen *Z*-Alkene gebildet.

Content

List of Abbreviations

AAD	acceptorless alcohol dehydrogenation	**Me**	methyl
cat.	catalyst	**MLC**	metal ligand cooperativity
DFT	density functional theory	**NaO*t*Bu**	sodium *tert*-butoxide
equiv	equivalents	**NMR**	*Nuclear Magnetic Resonance* (Kernspinresonanzspektroskopie)
Et	ethyl	***o***	*ortho*
***i*Pr**	isopropyl	***p***	*para*
IR	infrared	**ppm**	*parts per million*
KO*t*Bu	potassium *tert*-butoxide	**THF**	tetrahydrofuran

Units of Measurement

The International System of Units (SI) is utilised throughout this work to measure experimental or theoretical quantities. All derived units and their expression in terms of the SI base units are given below.

Quantity	**Unit**	**Name**	**Conversion to SI base units**
Temperature	°C	degree celcius	T/K = T/C° - 273.15 K
Volume	mL	millilitre	1 mL = 1 cm^3 = 10^{-6} m^3
Energy	kJ	kilojoule	1 kJ = $10^3 m^2 \cdot kg \cdot s^{-2}$
	calorie	calorie	1 cal = 4.2 Joules
Time	h	hour	1 h = 3600 s
	min	minute	1 min = 60 s
Frequency	cm^{-1}	wavenumber	1 cm^{-1} = 0.01 m^{-1}

List of Figures

List of Tables

List of Schemes

1 Target and Motivation

The economic importance of catalysis lies in the outstanding production of valuable products that can be found in all areas of our daily life and is demonstrated by the fact that approximately 80% of all processes within the chemical industry rely on catalysts.[1] Frequently, catalysts based on noble metals (e.g. palladium, rhodium, ruthenium, etc.) are applied in industry due to their high activities and selectivities in various catalytic transformations. However, noble metals are significantly less abundant in comparison to non-noble metals such as manganese, iron or cobalt.[2] Due to the high natural abundance of non-noble metals in the Earth's crust, they are considered as environmentally benign and are cheaper alternatives for cost-effective chemical processes and a more sustainable industry. In particular, manganese and iron are highly promising candidates, given their high biocompatibility and low cost.

In the context of this thesis, non-noble pincer complexes were investigated and applied to industrial relevant transformations. In more detail, transfer dehydrogenations and hydrogenation reactions were examined through the application of novel pincer catalysts based on nonprecious metals.

2 General Information – Iron and Manganese

Iron is the most abundant element on Earth by mass (32.1%), since it forms a significant proportion of the Earth's outer and inner core.[3] Furthermore, the Earth's crust is comprised of 5.6% iron, making it the fourth most abundant element by mass.[4] Here, it is mostly available as iron minerals such as hematite (Fe_2O_3), magnetite (Fe_3O_4) and siderite ($FeCO_3$).[5] Large deposits of iron ore usually occur in banded iron formations, which are thin layers of iron oxide minerals alternating with iron-poor rock layers.[6] To make the iron ore useful for industrial applications, metallic iron is currently produced by blast furnace processing of mineral iron.
Iron centers (specifically ions in oxidation states +II and +III) are involved in numerous biological systems within living organisms, for example as crucial components of metalloproteins, such as heme complexes, which are part of essential proteins including hemoglobin, myoglobin, and cytochromes.[7] In these systems, iron is involved in electron transfer reactions and oxygen transport within enzymes, which have been referred to as biological catalysts. Another class of iron-based organisms are the nonheme iron-based enzymes, including prominent examples like methane monooxygenase and ribonucleotide reductase.[8] It was therefore appropriate to take inspiration from these biological catalysts and develop iron-based complexes for catalysis. In industry, iron is highly prevalent as a catalyst, applied in the large-scale hydrogenation of adiponitrile and well-known procedures such as the Haber-Bosch and Fischer-Tropsch processes.[9] The most common iron oxidation states are +II and +III. However, the formal oxidation state range is from –II to +VI in different salts and complexes, thus offering interesting possibilities for redox catalysis.[10]

Manganese ranks as the twelfth most abundant element in the Earth's crust with a share of 0.095%.[4] Thereby, it is the third most abundant transition metal after iron and titanium. Typically, manganese occurs as a component of ores such as pyrolusite (MnO_2), braunite ($Mn^{2+}Mn^{3+}{}_6O_8SiO_4$), psilomelane ($(Ba,H_2O)_2Mn_5O_{10}$), and rhodochrosite ($MnCO_3$).[11] On an industrial scale, manganese ore is mostly used for the production of ferromanganese, an iron-manganese-alloy which is utilised in the steel industry, due to its deoxidising and sulfur-fixing properties, and the increased hardness of the alloy compared to pure steel.[11] Thus, steel production has accounted for a large portion of manganese demand (90%).[12] Further applications include aluminium-manganese alloys, and the complex methylcyclopentadienyl manganese tricarbonyl (MMT), which is used as an additive in unleaded gasoline to increase the octane rating.[13] Pure manganese is obtained by leaching manganese ore, followed by an electrowinning process from a manganese sulfate solution.[12]
Manganese-containing enzymes are omnipresent in the biosphere and play an important role in a number of biological processes. Several examples occur in the human body as

manganese cofactors are part of oxidoreductases, transferases, hydrolases, and isomerases, to name but a few.[14] Moreover, a metalloenzyme with a manganese core is a crucial part of the photosystem II, which is responsible for the oxidation of water during photosynthesis in plants.[15] Manganese displays a wide-ranging redox chemistry with oxidation states between –III and +VII.[11] Therefore, it has high potential as redoxcatalyst, but despite the use of manganese(IV) oxide for catalytic oxidations on industrial scale, other large scale applications are rare.[16] Nonetheless, synthetically important catalysts with manganese were developed by the groups of Jacobsen and Adkins. *Jacobsen's catalyst* is an asymmetric Mn (III) salen complex, which allows the enantioselective epoxidation of alkenes.[17] On the other hand, *Adkins' catalyst* is a heterogeneous catalyst, composed of $Cu_2Cr_2O_5$ doped with 2–3 wt% Mn oxides.[18] It enables the hydrogenation of fatty esters to the corresponding fatty alcohols.

Table 1. Comparison of palladium (exemplary for noble metals) with iron and manganese.

Criterion	Palladium	Iron	Manganese
Price[a]	2164 US$/t.oz	177 US$/t	Electrolytic (EMM), > 99,7 %: 1.553 US$/t
Abundance[b]	0.015 ppm 70th most abundant element	56000 ppm 4th most abundant element	950 ppm 12th most abundant element
Deposit	free metal	▪ hematite (Fe_2O_3) ▪ magnetite (Fe_3O_4) ▪ siderite ($FeCO_3$)	▪ pyrolusite (MnO_2) ▪ braunite (3 Mn_2O_3·$MnSiO_4$) ▪ psilomelane ($(Ba,H_2O)_2Mn_5O_{10}$) ▪ rhodochrosite ($MnCO_3$)

[a] Prices are average of 2020.[19,20] Iron ore (62% Fe): 110.0 US$/t. [b] Abundance in Earth's crust.[4b]

Owing to the high natural abundance of iron and manganese, both metals are relatively inexpensive (see Table 1), offering also environmentally friendly alternatives to precious metals for cost-effective catalyst synthesis. Consequently, significant progress has been made in the development of non-noble metal complexes for homogeneous catalysis in recent years.[21] In particular, in recent years pincer complexes play an important role due to their outstanding adaptability towards a vast range of catalytic applications.

3 Pincer Complexes

Pincer complexes feature a tridentate ligand system, which binds to three adjacent coplanar sites of a central metal atom, forming typically five- or six-membered chelate rings.[21] Thereby, pincer catalysts provide high stability and remarkably variable properties. In order to fine-tune the catalytic behaviour and gain high activity for various requirements, the ligand motif can be easily and systematically altered with respect to its steric and electronic properties (Figure 1).

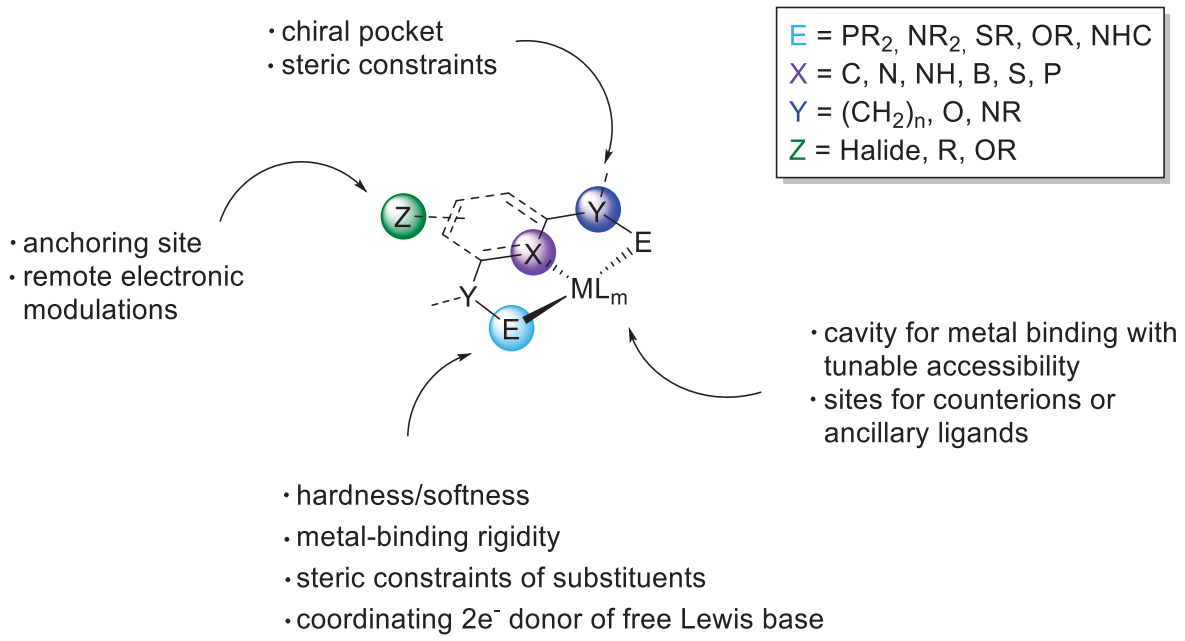
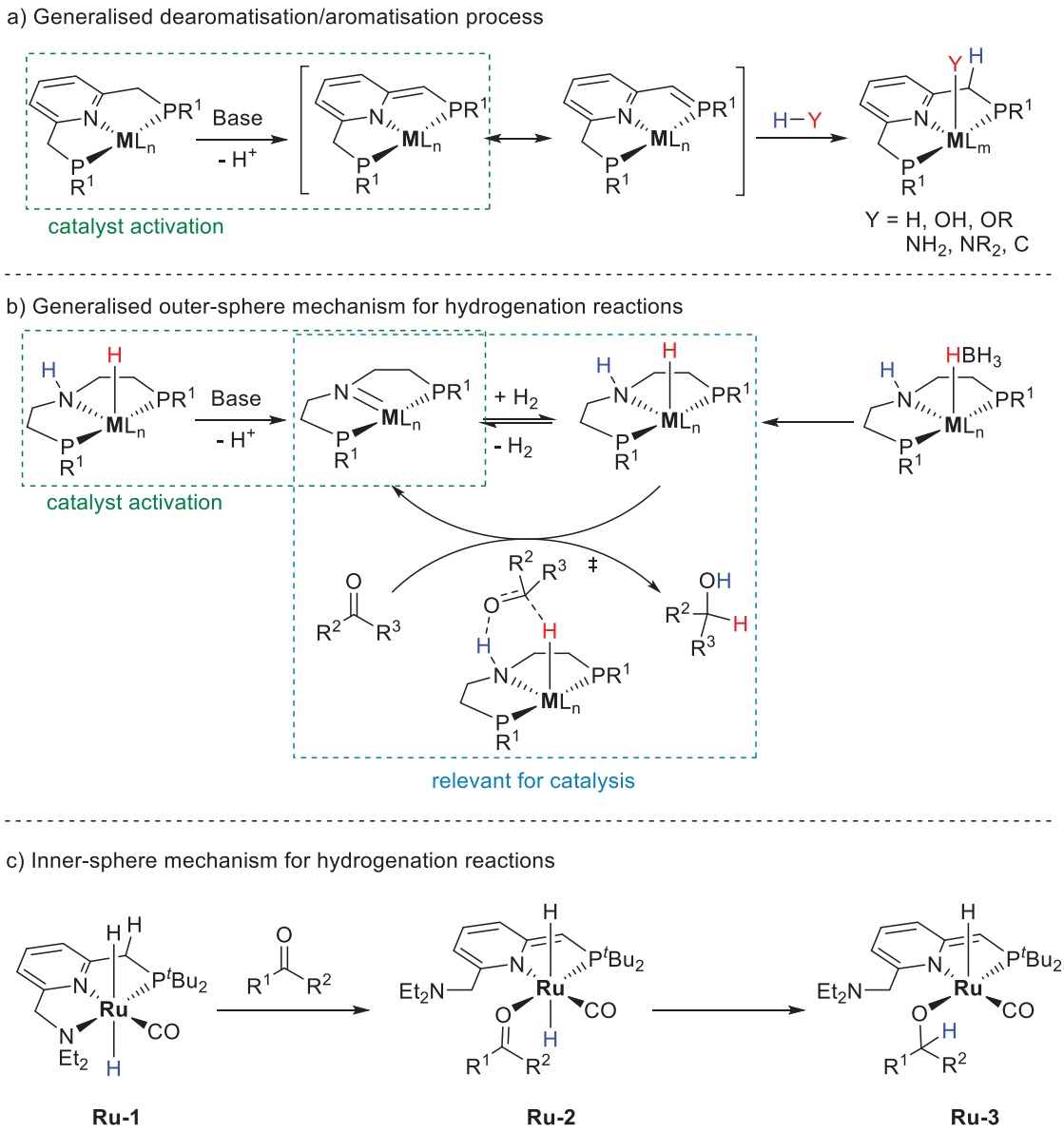


Figure 1. General structure of pincer complexes and potential modification sites in pincer ligands.[21]

Originally, pincer ligands were mainly so-called ECE type ligands comprised of an aryl ring, which is *ortho*-disubstituted by heteroatomic moieties (Figure 1, E). The meridional coordination mode results from the covalently bound aryl ring by a M-C σ-bond and the two substituents with donor atoms (N, P, S, O), which coordinate to the metal centre *via* dative bonds.[21] More recently, instead of the aryl ring, different pincer backbones have become well-known. Additional coordination modes of the pincer ligands such as mono- or bidentate, as well as facial coordination have been reported.[22]

A special characteristic of some pincer complexes is the capacity of the ligand to take actively part in the catalytic reaction as a so called non-innocent ligand. As a result, the formal oxidation state of the metal does not change because the ligand actively cooperates with the metal centre in bond-activation processes.[23] This so called metal-ligand cooperation (MLC) is presented in Scheme 1a where an aromatisation/dearomatisation process for a pincer complex bearing a pyridine backbone occurs.[24] The ligand backbone is dearomatised by base and

thereupon the dearomatised complex can activate a chemical bond (H–Y) such as H_2, or dehydrogenate substrates such as alcohols by C–H bond activation, correspondingly regaining aromatisation in both cases.



Scheme 1. Dearomatisation/aromatisation process[24], as well as outer[25c]- and inner-sphere[27] mechanisms for hydrogenation reactions.

Furthermore, an amine/amide pathway (Scheme 1b) is usually proposed for aliphatic pincer ligands. Two conceivable mechanisms, that are classified in the categories “inner-sphere” and “outer-sphere” have been described (Scheme 1b, 1c).[25] During an outer-sphere mechanism, the ligand is termed non-innocent and takes part in the catalytic cycle by the involvement of the amido function of the active catalyst during proton transfer. In this case, no direct interaction

between the metal centre and substrate is observed. For an overwhelming majority of (de)hydrogenation reactions with pincer complexes the outer-sphere mechanism is presumed.[26] On the contrary, the inner-sphere path involves the dissociation of a ligand (arm) to create a free coordination site, which enables the direct interaction between metal centre and substrate. A typical inner-sphere reaction mechanism is displayed in Scheme 1c for Ru PNN pincer complex **Ru-1** as an exemplary representation.[27,24b]

In addition to the high variability of the ligand, the metal centre also determines the properties of the complex. Initially, mainly noble metals of the platinum group were implemented in catalytic processes with pincer complexes.[28] However, the relatively high toxicity of precious metals and their limited availability, leading to rising prices, resulted in an increasing demand for non-noble counterparts. In the past two decades significant progress has been made developing pincer catalysts with non-noble metal centres such as manganese, iron, cobalt, and nickel.[25c,29] In the context of redox processes, the vast majority have been implemented for hydrogenation reactions, while dehydrogenations were rarely investigated.

4 Dehydrogenation of Alcohols by Non-Noble Metal Pincer Complexes

The dehydrogenation of alcohols with transition metal catalysts offers an attractive way to synthesise aldehydes and ketones.[30] These are valuable chemicals with a broad spectrum of applications in the laboratory, as well as in industry.[31] A rising interest in the exploitation of renewable resources makes the usage of bio-based alcohols as feedstock for important platform chemicals more likely in the future, depending on the profitability of the process. New synthetic routes for the selective oxidation of alcohols are therefore an interesting research area. Two varying approaches have been studied in this context: Acceptorless alcohol dehydrogenation (AAD) and transfer dehydrogenation with sacrificial hydrogen acceptors.[25c,32] Typically, alkenes or carbonyl compounds are suitable acceptors to take up the *in situ* formed hydrogen and in this way enable oxidations under milder conditions.[33] Over the past decade, considerable progress has been made in the development of pincer complexes, and in particular non-noble pincer catalysts for the dehydrogenation of alcohols have been explored.

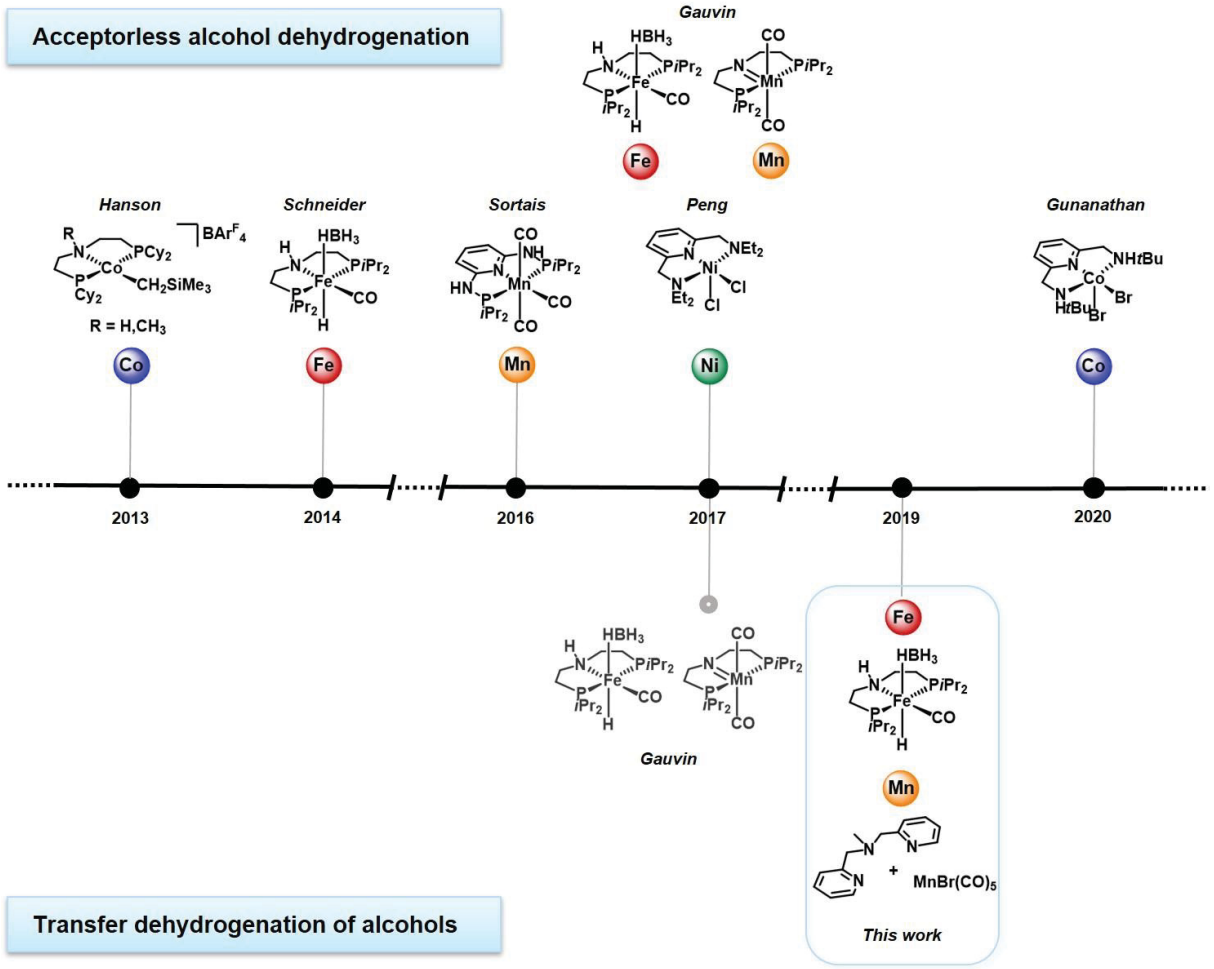
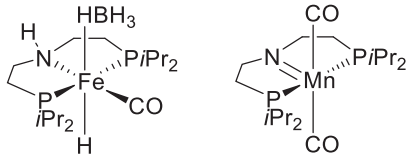


Figure 2. Timeline for the dehydrogenation of alcohols with non-noble pincer complexes.

An overview of the reported catalysts is displayed in Figure 2, with the majority applied for the acceptorless dehydrogenation of alcohols. In contrast, transfer dehydrogenations catalysed by pincer complexes have scarcely been explored. Hence, we focused our research on this area (see chapter 6.1 and 6.2).

4.1 Transfer Dehydrogenation of Alcohols

As described above, reports on the transfer dehydrogenation of alcohols with non-noble pincer complexes were exceptionally scarce. Prior to the first publication with manganese- and iron-based pincer catalysts, mainly iridium and rhodium complexes were applied for this transformation.[31,34] In 2017, Gauvin and co-workers published a report primarily describing the commercially available Ru-Macho-BH catalyst for the dehydrogenation of butan-1-ol to butanal.[35]



Fe-1 **Mn-1**

Gauvin

Figure 3. Non-noble metal pincer complexes applied in the transfer dehydrogenation of alcohols.

The oxidation proceeded with 1 mol% catalyst loading at 60 °C in the presence of a large excess of acetone as both hydrogen acceptor and solvent. Without the excess acetone, side products such as butyl butyrate were observed. Further attempts to use base-metal pincer complexes **Fe-1** and **Mn-1** under the same reaction conditions showed only 2% and 6% butanal respectively (Figure 3). Notwithstanding, it should be cited as the first report of a transfer dehydrogenation with non-noble pincer complexes, to which our research is linked.

4.2 Acceptorless Dehydrogenation of Alcohols

The first example for the acceptorless dehydrogenation of alcohols with a non-noble metal pincer catalyst was reported by the group of Hanson in 2013.[36] Two cobalt complexes featuring a non-methylated PNP ligand (**Co-1**) and a *N*-methylated PNP ligand (**Co-2**) showed, respectively, 90 and 95% yield of acetophenone in the dehydrogenation of 1-phenylethanol (Figure 4).

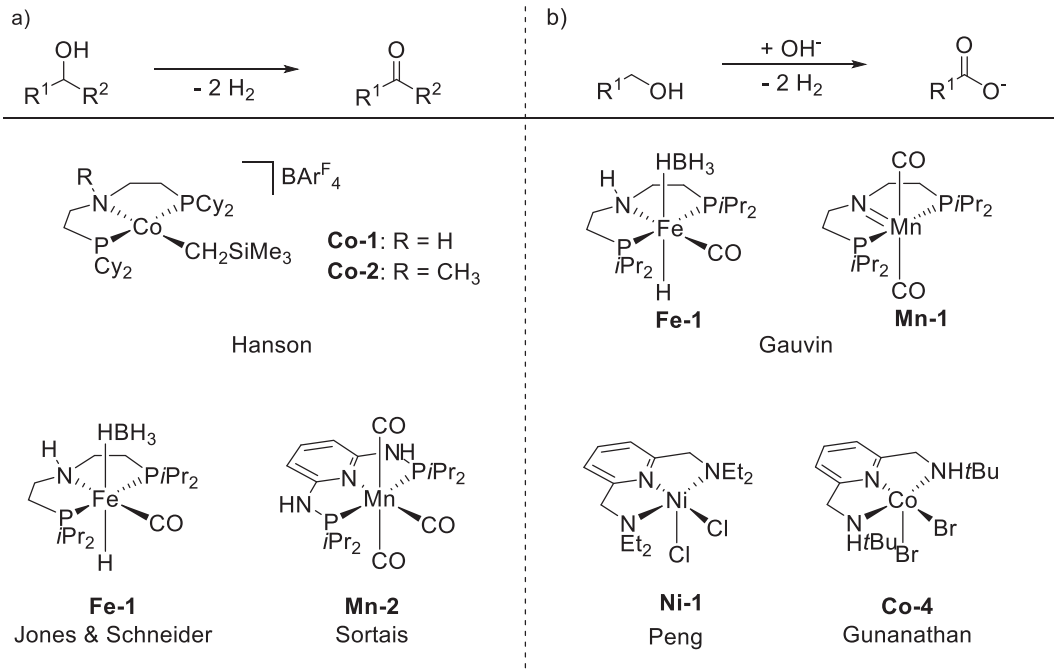
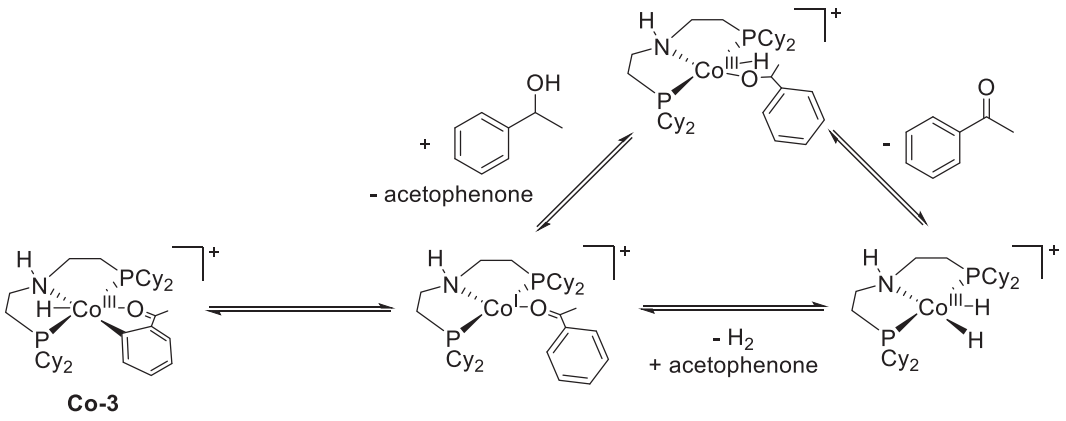


Figure 4. Non-noble pincer complexes applied for the acceptorless dehydrogenation of alcohols.

Due to the similar activity of **Co-1** and **Co-2**, Zhang *et al.* proposed that the *N*-H moiety of the pincer backbone does not play a crucial role for the reaction. The isolation of complex **Co-3** as the active intermediate and further NMR experiments revealed that the reaction proceeds *via* a cobalt(I)/cobalt(III) cycle (Scheme 2). The general applicability of the precatalyst **Co-1** was showcased by the successful dehydrogenation of several secondary alcohols.

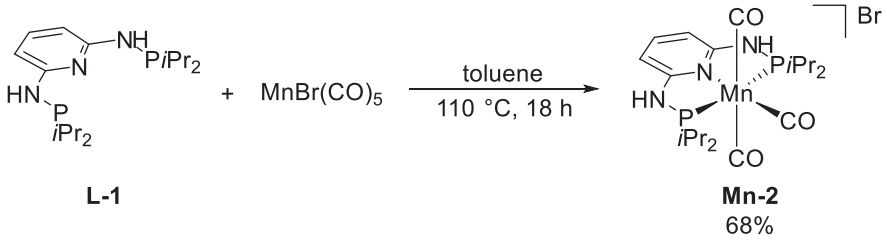


Scheme 2. Proposed mechanism of cobalt-catalysed dehydrogenation of 1-phenylethanol.[36]

The first AAD catalysed by an iron pincer complex, were reported by the groups of Jones and Schneider in 2014.[37] Using 1 mol% of complex **Fe-1** under base-free conditions, the AAD of a variety of benzylic and aliphatic secondary alcohols were effectively catalysed. Notably,

primary alcohols were selectively dehydrogenated to the respective esters and primary diols were successfully oxidised, furnishing the corresponding lactones. The authors used DFT calculations to investigate the possible mechanism of the AAD, indicating the crucial role of metal-ligand cooperation in this reaction.

Later on, Sortais and co-workers demonstrated that manganese based pincer complexes are also suitable catalysts for dehydrogenation.[38] Complex **Mn-2** was synthesised in 68% yield by reacting $MnBr(CO)_5$ and pincer ligand **L-1**, which features a 2,6-(diaminopyridinyl)diphosphine scaffold, in refluxing toluene (Scheme 3). However, the authors mainly focused on hydrogenation, and 1-phenylethanol was the only example of an AAD reaction catalysed by **Mn-2**. Applying a catalyst loading of 5 mol% **Mn-2** and 10 mol% KO*t*Bu, acetophenone was obtained in 84% yield after 22 h in toluene at 110°C.



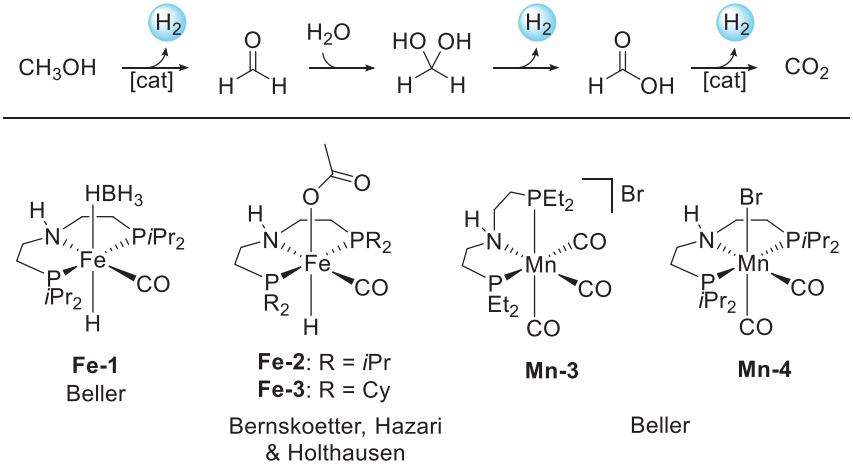
L-1 **Mn-2** 68%

Scheme 3. Synthesis of manganese PNP complex **Mn-2** reported by Sortais and co-workers.[38]

In the following years, the acceptorless dehydrogenation of primary alcohols to carboxylic acid (salts) received significant interest. The first example of a non-noble metal catalyst performing this class of reactions was reported by the group of Gauvin in the above-mentioned publication from 2017.[35] The reaction conditions were optimised for the dehydrogenation of butanol, and applied to other bio-sourced alcohols such as fatty and terpenoic derived alcohols. Initially, the reaction was conducted with 2 mol% catalyst loading (**Fe-1** or **Mn-1**) in the presence of 2 equiv water and 1.1 equiv KOH in toluene at 120 °C. However, in the absence of water, the catalytic activity of **Fe-1** and **Mn-1** was significantly increased. Butyric acid was isolated in excellent yields (95–96%) after 24 h and 6 h, respectively. Shortly after the work of Gauvin, Peng's group further investigated the acceptorless dehydrogenation of primary alcohols and published a new phosphorus-free nickel NNN pincer complex (**Ni-1**).[39] The described methodology operates with 1 mol% **Ni-1** in the presence of 25 mol% of the respective sodium alkoxide. Several *meta*- and *para*-substituted benzyl alcohol derivatives were readily dehydrogenated with yields ranging from 60% to 90% after 48 h at 150 °C. More recently, Gunanathan and co-workers used a cobalt catalyst with a phosphorus-free NNN pincer ligand (**Co-4**) to produce carboxylate salts from the corresponding primary alcohols. Overall, a broad variety of (hetero)aromatic and aliphatic alcohols were oxidised using 2 mol% **Co-4** and 1.5 equiv KOH in toluene at 140 °C

for 16 h. The carboxylic acid salts were obtained after an acidic workup with 1 M HCl in low to excellent yields (27–95%). Notably, various challenging functionalities such as nitro, amine and methoxy groups, as well as internal alkenes were well tolerated.

Besides the purpose of alcohol dehydrogenation for synthetic use, alcohols such as methanol can be used as a hydrogen storage medium, and the release of this hydrogen is the primary objective of the dehydrogenation reaction.[40] In fact, hydrogen storage is a significant topic in social and political debate, and methanol is often discussed as a liquid organic hydrogen carrier (LOHC). This stems from the fact that methanol has a high gravimetric hydrogen content of 12.6wt% and offers the possibility of circumventing the safety issues encountered during storage and transportation of hydrogen gas.[41] With regard to pincer complexes, the main focus of research has been on aqueous methanol reforming. The dehydrogenation to H_2 and CO_2 proceeds through three reaction steps with formaldehyde, methylene glycol, and formic acid as the intermediates of the overall reaction (Scheme 4). Thus, dehydrogenation of formic acid is also part of ongoing research and presented in more detail in current reviews, however it is not discussed in this work.[41,42]



Scheme 4. Non-noble pincer catalysts applied in the acceptorless dehydrogenation of methanol.

The first iron pincer catalyst applied to the acceptorless dehydrogenation of methanol was reported by the group of Beller in 2013.[43] In this publication the aforementioned complex **Fe-1** was presented, and the synthesis was described for the first time (Scheme 4). Although hydrogen evolution could be obtained without the use of a base, ancillary KOH significantly increased the catalyst activity. By lowering the catalyst loading to 1 µmol, and with 8 M KOH present in a MeOH/H_2O mixture (4:1) at 91 °C, a TON up to nearly 10000 was achieved after 46 h. Following this work, the groups of Bernskoetter, Hazari and Holthausen showed the related formate complex **Fe-2** and improved the catalytic performance by using a co-catalytic

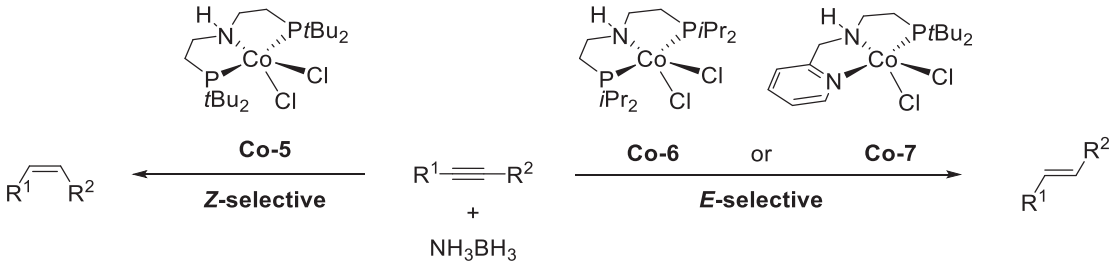
amount of a Lewis acid (10 mol% $LiBF_4$).[44] In this way, full conversion was achieved with 0.03 mol% catalyst loading in a MeOH/H_2O mixture (4:1), and ethylacetate as co-solvent at 78 °C after 39 h. Interestingly, lowering the catalyst loading to 0.006 mol% resulted in a TON of 51000 after 94 h. However, the yield was lowered by half under these reaction conditions. Following the works with iron pincer complexes, manganese based pincer catalysts were implemented by Beller and co-workers for aqueous methanol dehydrogenation in 2017.[45] The reported cationic complex **Mn-3** has a pincer ligand, which coordinates the metal centre in an unusual *facial* fashion. Application of 8 µmol **Mn-3** with 8 M KOH at 92 °C for 5 h gave a TON of 65. Similarly, the neutral Mn PNP complex **Mn-4** bearing isopropyl substituents on the phosphorus atoms was found to achieve a TON of 54. Notably, remarkable long-term stability of more than a month was attained in the presence of additional 10 equiv of PNP*i*Pr ligand and a TON over 20000 was obtained, which is a superior result in comparison to the related iron based complex **Fe-1**.

5 Hydrogenation of Alkynes by Non-Noble Metal Pincer Complexes

The transition metal mediated semihydrogenation of alkynes to the corresponding alkenes is an interesting transformation in homogeneous catalysis. More specifically, *Z*-alkenes are a widespread motif in biologically active compounds, as well as in pharmaceuticals and fragrances.[46] Being highly prevalent in the scaffold of organic compounds, a number of synthetic approaches have been developed in the past, but the selective C–C triple bond reduction constitutes the most convenient method towards selective *Z*-alkenes.[47] A classical and facile catalytic system, which is frequently employed on laboratory and industrial scale, is the Lindlar catalyst. The lead and quinoline-poisoned palladium on $CaCO_3$ is able to promote the semihydrogenation furnishing exclusively *Z*-alkenes.[48] However, it has drawbacks such as using environmentally harmful $Pb(OAc)_2$ during the preparation, and as a result catalyst recycling is elaborate and expensive.[49] Moreover, noble metals have increasingly been avoided over the last decade, due to their limited availability and higher price. In this respect, several homogeneous pincer complexes based on non-noble metals were reported for the semihydrogenation of alkynes. In general, two different concepts were followed: Hydrogenation with molecular hydrogen, and transfer hydrogenation realised by using hydrogen donors, for instance ammonia borane or methanol.

5.1 Transfer Semihydrogenation of Alkynes

In 2016, the group of Liu published three different cobalt pincer complexes (**Co-5**–**Co-7**), which promote the stereodivergent transfer semihydrogenation of alkynes by utilising ammonia borane (NH_3BH_3) as the hydrogen source.[50] Depending on the ligand used, either *Z*- or *E*-alkenes were obtained with high yields and good selectivities (Scheme 5).



Scheme 5. Stereodivergent cobalt-catalysed transfer semihydrogenation of alkynes.[50]

The *E*-isomer is obtained *via* a *Z*- to *E*-isomerisation process, which was proven by a kinetic profile. Interestingly, the *Z*-alkene is the intermediate of the reaction and the progression of the isomerisation is inhibited by the substrate. After complete consumption of the alkyne, the rate

of the isomerisation exhibited a sharp increase. This process takes place on an open coordination site of the catalyst if the metal centre is sterically less hindered. Owing to bulky *t*-butyl substituents at the phosphorus atoms of the PNP ligand of complex **Co-5**, no isomerisation occurs and the formation of the *Z*-isomers is favoured. Notably, a small modification of the substitutents of the PNP ligand to *i*-propyl (**Co-6**) resulted in a totally different stereoselectivity and primarily led to *E*-alkenes (12:1 *E*/*Z*). Moreover, a cobalt NNP pincer complex (**Co-7**) was reported, which showed even higher selectivity towards *E*-alkenes (>99:1 *E*/*Z*), demonstrating the beneficial effect of the pyridine coordination site. While the general applicability for **Co-5** and **Co-6** was proven by the semihydrogenation of various internal alkynes with good yields and stereoselectivities, catalyst **Co-6** showed superior activity for terminal alkynes in a smaller substrate scope. Furthermore, outstanding versatility regarding internal and terminal alkynes was achieved by Landge *et al.* in 2018 using the phosphorus-free cobalt NNN pincer pre-catalyst **Co-8** and ammonia borane, which was applied to transform various alkynes to the corresponding *Z*-alkenes (Figure 5).[51]

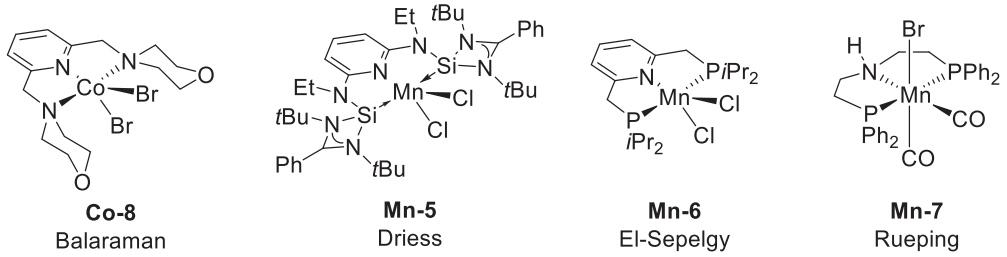


Figure 5. Non-noble metal pincer-based catalysts for the transfer semihydrogenation of alkynes.

The first example of a manganese catalysed transfer semihydrogenation was reported by Driess and co-workers.[52] The precatalyst (**Mn-5**) bearing a pincer-type bis(NHSi)-pyridine ligand showed best activity with ammonia borane as the hydrogen source, leading to high yields and *E*-alkenes as the main products. In the same year, the group of El-Sepelgy published a manganese PNP complex (**Mn-6**), which was capable of reducing 18 different internal alkynes to give the corresponding *Z*-alkenes, generally in high yield and good selectivity.[53] The latter two catalyst systems worked with 1 mol% catalyst loading and 1 equiv NH_3BH_3 at relatively low temperatures (55–60 °C). Recently, Rueping's group demonstrated alkyne reduction with the use of MeOH as the hydrogen source.[54] Upon activation with Cs_2CO_3, the manganese based pincer catalyst (**Mn-7**) proved to be active for the semihydrogenation of a variety of different alkynes to the *Z*-alkenes. However, high temperature of 150 °C was shown to be necessary for the transformation.

5.2 Semihydrogenation of Alkynes

The first example of a non-noble metal pincer complex applied in the semihydrogenation of alkynes was published by the group of Milstein in 2013 (Figure 6).[55] Using an acridine-based iron PNP complex with an amidoborane ligand (**Fe-4**), sixteen different alkynes were successfully hydrogenated to the corresponding *E*-alkenes in high yields without additional base. Notably, high selectivity of the *E*-isomers (up to 100:0 *E*/*Z*) was obtained due to fast *in situ* isomerisation of the initially formed *Z*-alkenes.

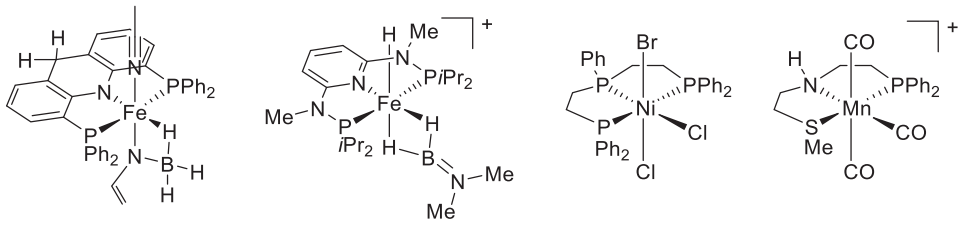


Figure 6. Non-noble metal pincer-based catalysts for the semihydrogenation of alkynes.

In a related fashion, high *E*-selectivity was attained by Fout and co-workers with the cobalt CCC pincer catalyst **Co-9** (Figure 7).[56] A variety of terminal alkynes were efficiently reduced with 1 to 3 mol% catalyst loading under mild conditions (4 atm H_2, 30 °C, THF) and furnished the desired alkenes in good yields. A further publication reported related complexes with modified pincer ligands.[57] Compared to **Co-10**, complex **Co-11** was substituted in the *para*-position of the aryl backbone with a *tert*-butyl group, while catalyst **Co-12** was equipped with a trifluoromethyl moiety at the same position. The reactivity of **Co-11** was similar to the activities obtained with **Co-9** and **Co-10**. However, the loss of electron densitiy at the metal centre by the electron-withdrawing trifluoromethyl group, led to reduced activity of the catalyst **Co-12**, resulting in lower product selectivity.

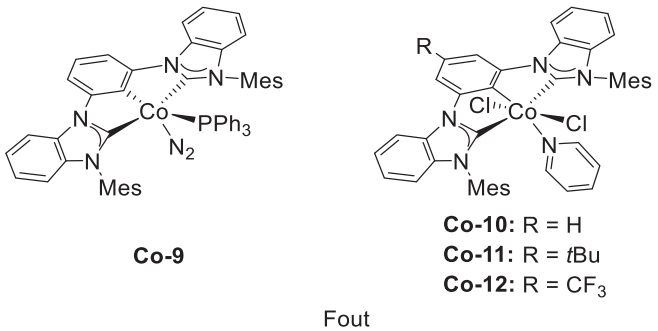


Figure 7. Cobalt based pincer complexes for the semihydrogenation of alkynes.

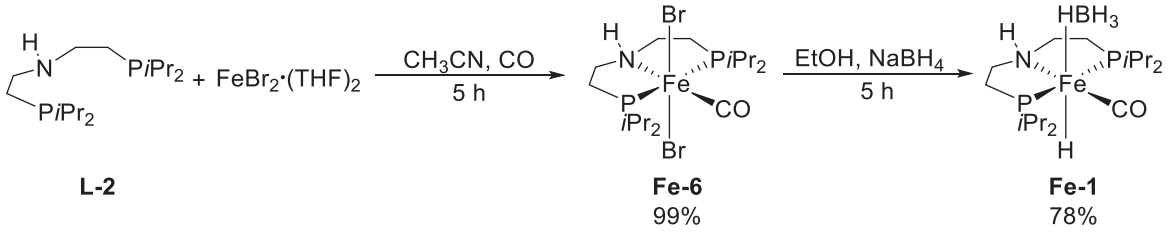
Another iron PNP pincer complex (**Fe-5**) was reported by the group of Kirchner in 2019 (Figure 6).[58] The applied Fe catalyst contains an aminoborane ligand, which is labile and provides two vacant coordination sites on the catalyst after dissociation. Hence, precatalyst **Fe-5** efficiently catalysed the reduction of internal alkynes, as well as 1,3-diynes and 1,3-enynes to the respective *Z*-alkenes under mild conditions (1 h, 25 °C, 4–5 bar H_2). In 2019, Beller and co-workers described the first nickel based pincer complex (**Ni-2**).[59] Despite a heterogeneous methodology with nickel nanoparticles providing only *Z*-alkenes, a molecular defined Ni triphos catalyst was reported for the selective production of *E*-isomers *via* a hydrogenation/isomerisation mechanism. Very recently, the group of Rueping disclosed an air-stable manganese PNS pincer catalyst (**Mn-8**) for the semihydrogenation of alkynes with molecular hydrogen.[60] The previously described catalyst **Mn-7** was published simultaneously and used for transfer semihydrogenation with MeOH, exhibiting a 50% lower activity than **Mn-8**. For the substrate scope, 1–2 mol% catalyst loading in combination with 2.5 equiv KO*t*Bu (referred to the catalyst loading), 60 °C, and 20 bar H_2 was used. Reaction times between 12 h and 24 h in toluene were required to implement the substrate scope. Overall, 25 substrates including (hetero)aromatic and aryl-alkyl alkynes, were selectively hydrogenated to the corresponding *Z*-alkenes and allylic alcohols in high yields. Furthermore, a gram scale synthesis was accomplished with 0.5 mol% **Mn-8** and 1.25 mol% KO*t*Bu, furnishing *Z*-stilbene in 99% yield after a 16 h reaction time.

6 Results and Discussion

6.1 Iron PNP-Pincer-Catalysed Transfer Dehydrogenation of Secondary Alcohols

As described in the introduction, in recent years the scientific focus of sustainable redox chemistry in pincer catalysis has mainly been on the application of non-noble metal pincer complexes in catalytic hydrogenations. This raised the question of whether the same activity of iron- and manganese-based pincer complexes could be obtained for the corresponding dehydrogenation reactions. Based on previous work performed in our group regarding the dehydrogenation of methanol using a molecularly defined iron PNP pincer complex (**Fe-1**, Scheme 6), we became interested in developing a general methodology applicable to a broader scope of alcohols.[43] In order to run the reaction under mild conditions, acetone was used as inexpensive hydrogen acceptor, thus facilitating the dehydrogenation reaction.[61]

Complex **Fe-1** was synthesised according to a procedure reported in literature, starting from the precursor $FeBr_2(THF)_2$ and pincer ligand *bis*(2-diisopropylphosphinoethyl)amine **L-2**.[43] Under an atmosphere of CO (1 atm), the dark blue complex **Fe-6** was formed and isolated in quantitative yield (99%). This precatalyst, however, was not able to promote the desired dehydrogenation of 1-phenylethanol (**1a**). Therefore, we prepared the hydrido hydroborato complex **Fe-1** by treating complex **Fe-6** with an excess of $NaBH_4$ in ethanol. Using this procedure, the bright yellow complex **Fe-1** was obtained in 78% yield (Scheme 6).



L-2 **Fe-6** 99% **Fe-1** 78%

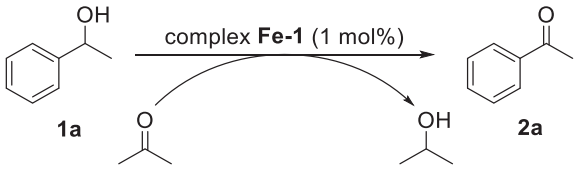
Scheme 6. Synthesis of iron PNP complex **Fe-1**.

Due to the facile dissociation of BH_3, the active hydride complex can be formed *in situ* without base.[62] However, the use of an ancillary base showed an accelerating effect on the catalytic activity in the case of the dehydrogenation of methanol with the same pincer complex.[43] Hence, we tested 1 mol% catalyst loading in the presence of 5 mol% NaO*t*Bu as additive. Interestingly, we were able to detect an increase in yield of acetophenone (**2a**) from 12% to 89% after a 19 h reaction time at 70 °C (Table 2, Entries 1–2). However, complete consumption

of the starting material was already achieved after 4 h, resulting in the formation of desired product acetophenone (**2a**) in 91% yield (Table 2, Entry 3).

Moreover, reducing the temperature to 50 °C resulted in similar catalytic activity (Table 2, Entry 4). In order to provide better comparability by reducing the conversion to below 100%, the experiments for optimising base and solvent were conducted with a 2 h reaction time. As a result, KO*t*Bu and *n*-heptane proved to be the best choice (Table 2, Entries 5–8).

Table 2. Optimisation of the 1-phenylethanol dehydrogenation reaction conditions with complex **Fe-1**.[a]



Entry	Base[b]	t [h]	T [°C]	Solvent[c]	Conv. [%]	Yield [%]
1	-	19	70	THF	14	12
2	NaO*t*Bu	19	70	THF	100	89
3	NaO*t*Bu	4	70	THF	100	91
4	NaO*t*Bu	4	50	THF	97	93
5	NaO*t*Bu	2	50	THF	57	53
6	NaO*t*Bu	2	50	heptane	84	73
7	KO*t*Bu	2	50	heptane	94	84
8	KO*t*Bu	4	50	heptane	100	97
9[d]	NaO*t*Bu	2	50	heptane	0	0
10[d,e]	NaO*t*Bu	2	50	heptane	17	13
11[e]	NaO*t*Bu	2	50	heptane	83	71

[a] Conversion and yield were determined by GC using hexadecane as an internal standard. [b] 5 mol% base loading. [c] 2.5 mL solvent, 2.5 mL acetone. [d] Reaction was carried out without acetone. [e] Reaction was carried out in an open system.

Having acceptorless dehydrogenation as a competitive reaction pathway in mind, we were interested as to whether the reaction takes place without acetone under the optimised reaction conditions. A lack of activity within the reaction was observed when the experiment was carried out in a closed flask (Table 2, Entry 9). However, acceptorless dehydrogenation is usually conducted in an open system to release the produced hydrogen and shift the equilibrium towards the products.[37] Under these conditions, only 17% conversion was detected, yielding 13% acetophenone (**2a**) (Table 2, Entry 10). When the experiment was performed again using acetone, an enhanced yield of 71% was attained, comparable to the reaction in a closed

system. (Table 2, Entries 6 and 11). The conducted experiments demonstrate that a hydrogen acceptor facilitates the alcohol dehydrogenation, thus allowing for milder reaction conditions. Additionally, this was supported by DFT calculations, using the B3PW91 density functional theory (Figure 8). A potential outer-sphere mechanism was proposed, consisting of the dehydrogenation of 1-phenylethanol (**1a**) to acetophenone (**2a**) by the amido complex **Fe-1a**, which is transformed into the amine complex **Fe-1b**. In the second step the amido complex **Fe-1a** is regenerated back to **Fe-1b** and acetone takes up the hydrogen to form isopropanol. As a side reaction, the amine complex **Fe-1b** can release H_2 to form the amido complex **Fe-1a** without the involvement of an acceptor, and in this case only the substrate is oxidised. These results agree with the hydrogen evolution confirmed by GC-MS.

The hydrogenation of acetone to isopropanol is exothermic (ΔG_2) by 12.7 kJ mol^{-1} with a barrier ($\Delta G_2^{\ddagger}$) of 90.0 kJ mol^{-1}. It was shown that the total transfer dehydrogenation is exothermic (ΔG_{tot}) by 4.0 kJ mol^{-1} with a computed equilibrium constant of 4.43. Due to this, an excess of acetone is necessary in order to shift the balance of the reaction in the direction of the products. In contrast, without a hydrogen acceptor the dehydrogenation is endergonic (ΔG_1) by 8.7 kJ mol^{-1}, which validates the lack of activity of the catalytic system without acetone in a closed system (Table 2, Entry 9).

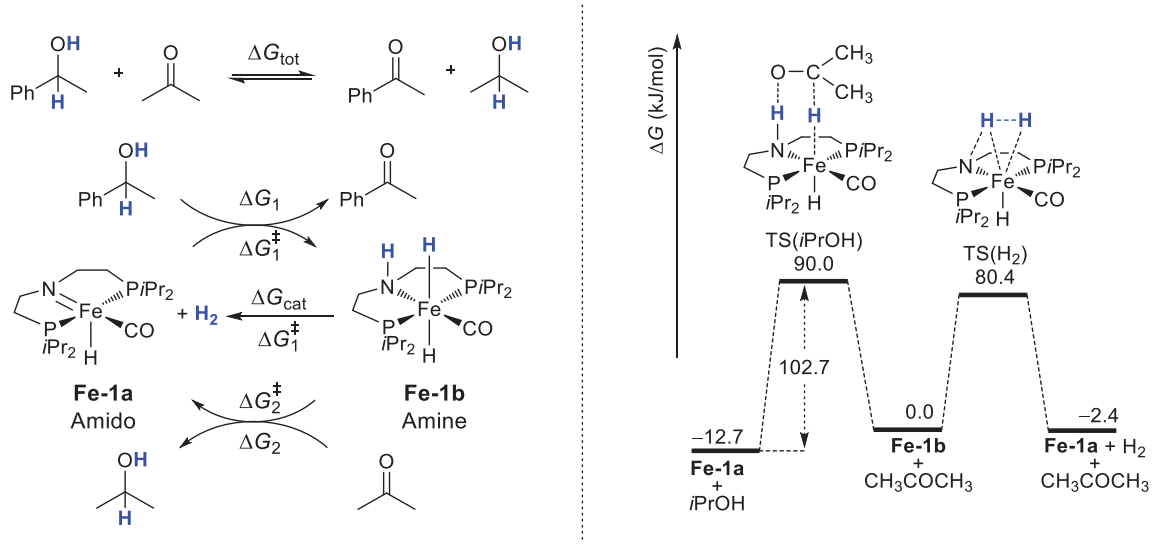


Figure 8. Proposed reaction sequences for the benchmark dehydrogenation 1-phenylethanol (left), and the reaction coordinates for the interconversion of catalysts [**Fe-1b**=**Fe-1a**+H_2] and hydrogen acceptor [acetone+H_2=isopropanol] (right).

Moreover, in an open system the release of H_2 was considered, and the acceptorless dehydrogenation of 1-phenylethanol (**1a**) to acetophenone (**2a**) and H_2 was found to be endergonic by 6.3 kJ mol^{-1}. The marginal endergonic acceptorless dehydrogenation requires higher temperatures to accelerate the reaction and achieve a decent yield, whereas the

transfer dehydrogenation with acetone is exergonic by 4.0 kJ mol^{-1} and can be performed under milder conditions (Table 2, Entries 6 and 10). Overall, the computational studies support the beneficial effect of acetone, which shifts the endergonic acceptorless dehydrogenation to an exergonic transfer dehydrogenation.

With optimised conditions in hand (1 mol% **7**, 5 mol% KO*t*Bu, 50°C, 4 h, 5 mL heptane, 5 mL acetone), we studied the general applicability of our catalytic system for the dehydrogenation of various alcohols. Benzylic alcohols with electron-withdrawing, as well as electron-donating groups in *para*- or meta-position were readily converted to the corresponding ketones in good to excellent isolated yields (Scheme 7, **2a**–**i**). In the case of *ortho*-substituted 2'-chloro-1-phenylethanol (**2k**), the observed drop of activity could be explained by the increased steric hindrance of the substrate. Interestingly, a selective dehydrogenation of the hydroxyl group is observed for substrate **2g** bearing an amino functionality, which is not oxidised during the catalytic reaction.

Additionally, by way of example, selected substrates were fully dehydrogenated to the corresponding ketones with only 0.1 mol% catalyst loading after 24 h (**2a**, **2b** & **2d**), whereas 4'-bromoacetophenone (**2d**) was detected in 91% yield by using only 0.25 mol% of catalyst.

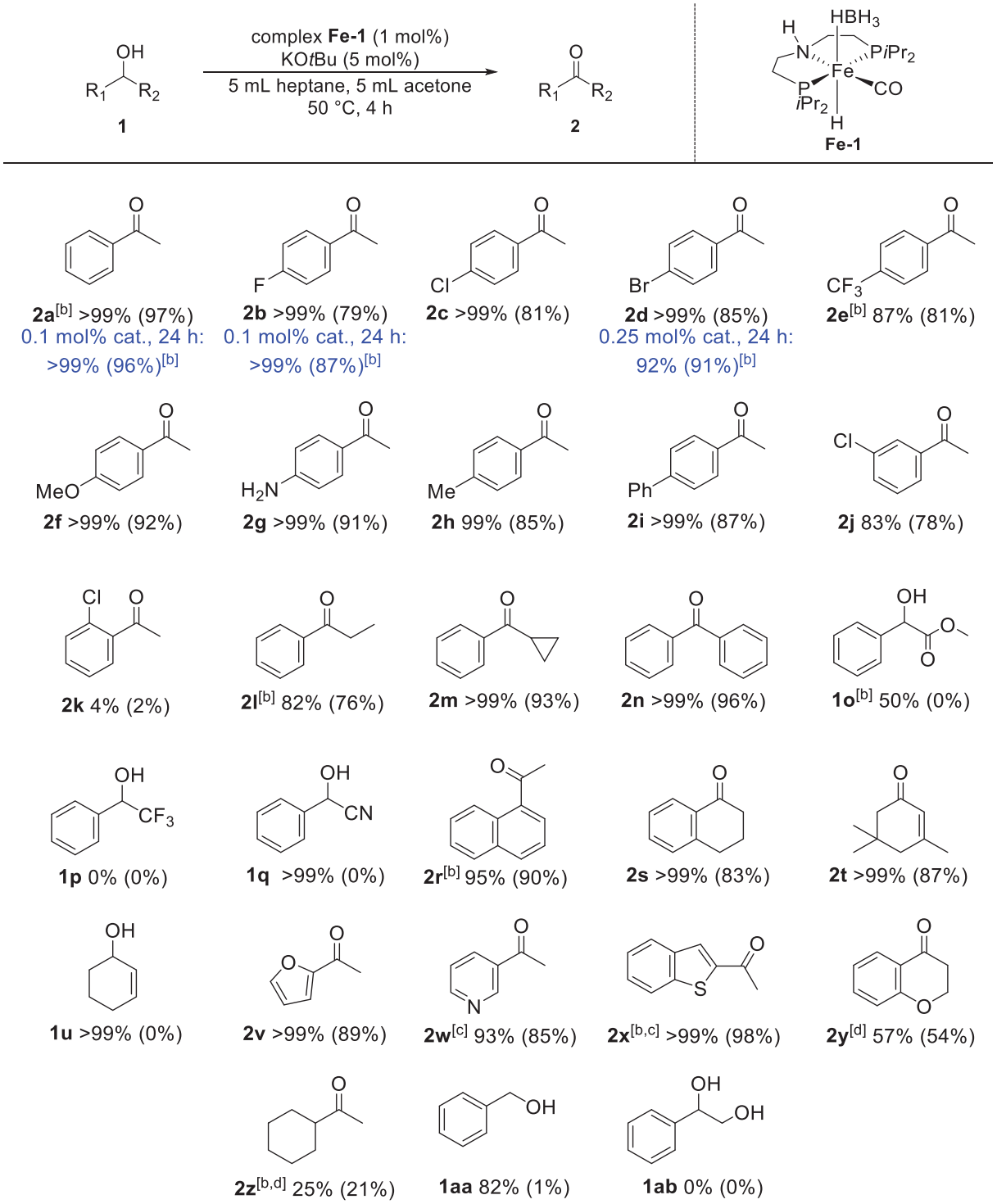
Moreover, ketones bearing sterically demanding substituents in α-position to the carbonyl function were isolated in yields ranging from 76% to 96%, without harsh conditions being required (**2l**–**n**). Application of substrate **2o** bearing a methyl ester group resulted in cyclic ketal formation, which is already reported in literature, and 50% of 2,2-dimethyl-5-phenyl-1,3-dioxolan-4-one is observed.[63] In the case of 2,2,2-trifluoro-1-phenylethanol (**1p**), the strong electron-withdrawing effect of the trifluoromethyl group causes a lack of activity in the catalytic system. Mandelonitrile (**1q**) was fully converted to benzaldehyde.

Examplarily for annulated arenes, 1-(naphthalen-1-yl)ethanol (**1r**) was dehydrogenated with 95% conversion and 90% yield. Likewise, full conversion of α-tetralol (**1s**) was achieved, furnishing the desired product with 83% yield.

Additionally, allylic alcohols can be smoothly oxidised under optimised conditions as demonstrated for 3,5,5-trimethylcyclohex-2-en-1-ol (**1t**). However, in order to circumvent the competing Michael addition, the β-position to the hydroxyl group has to be blocked. In the case of 2-cyclohexen-1-ol (**1u**) full conversion was observed, yielding 46% of 3-acetonylcyclohexan-1-one besides other unidentifiable side products by GC-MS analyses.

Notably, heteroaromatic substrates were effectively dehydrogenated as well. The corresponding ketones were obtained with yields ranging from 54% to 98%. (**2v**–**y**).

To further probe the general applicability of the catalytic system toward aliphatic alcohols, we tested the dehydrogenation of 1-cyclohexylethanol (**1z**). Despite higher catalyst loading and raised reaction temperatures, only modest activity was observed.



Scheme 7. Substrate scope and limitations for the dehydrogenation of alcohols using **Fe-1**.[a]

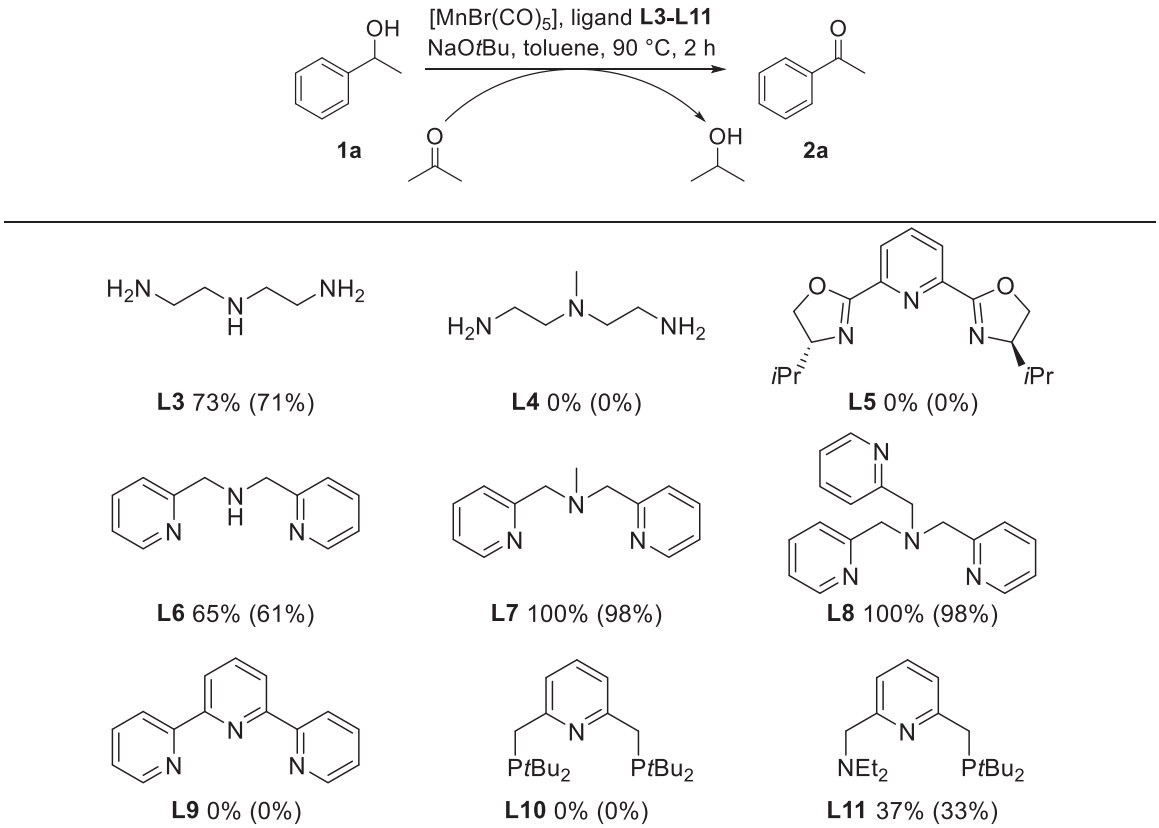
Conversions were determined by GC using hexadecane as an internal standard. Isolated yield is given in parentheses. [a] Reaction conditions: substrate (1 mmol), complex **Fe-1** (0.01 mmol), KO*t*Bu (0.05 mmol), heptane (5 mL), acetone (5 mL), 50 °C, 4 h. [b] GC yield. [c] Reaction conditions: substrate (1 mmol), complex **Fe-1** (0.02 mmol), KO*t*Bu (0.1 mmol), heptane (5 mL), acetone (5 mL), 50 °C, 24 h. [d] Reaction conditions: substrate (1 mmol), complex **Fe-1** (0.02 mmol), KO*t*Bu (0.1 mmol), heptane (5 mL), acetone (5 mL), 80 °C, 24 h.

Additionally, we attempted the dehydrogenation of primary alcohols, e.g. benzyl alcohol (**1aa**), which resulted in various side reactions with acetone or *iso*-propanol. Indeed, a base-catalysed aldol reaction was already observed for all reactions beforehand, however only two molecules of acetone reacted with each other forming diacetone alcohol and 4-methylpent-3-en-2-one *via* aldol addition and aldol condensation, respectively. Consequently, conversions and yields were unaffected by this. However, the higher reactivity of the *in situ* obtained benzaldehyde (**1aa**) led to the formation of 4-phenyl-3-buten-2-ol (6%) and the corresponding ketone, 4-phenyl-3-buten-2-one (46%). Additionally, 28% of 5-methyl-1-phenylhexa-1,4-dien-3-one, formed during the aldol condensation of benzaldehyde and mesityl oxide, was detected by GC-FID analyses. In conclusion, when acetone is used as a hydrogen acceptor, primary alcohols are not suitable substrates for the catalytic dehydrogenation. However, application of different acceptors including benzophenone, benzil, benzalacetophenone, and 3,3-dimethyl-1-butene resulted in no conversion and therefore are unsuitable for the intended dehydrogenation methodology in general.

Furthermore, 1-phenyl-1,2-ethanediol (**1ab**) was used as a substrate to examine possible selectivity towards the dehydrogenation of the secondary alcohol moiety. Surprisingly, no dehydrogenation took place. Further insights into the origin of this absence of activity were gained by conducting an experiment with the benchmark substrate 1-phenylethanol (**1a**) and diol **1ab** with double the amount of catalyst and base. Under these conditions, 1-phenylethanol (**1a**) was not dehydrogenated. Based on these observations, we believe that the diol acts as a catalyst poison, e.g. by blocking the active site of the complex.

6.2 Transfer Dehydrogenation of Secondary Alcohols Catalysed by Manganese NNN-Pincer Complexes

As part of our ongoing interest in the transfer dehydrogenation of alcohols and the newly emerging developments of manganese based pincer complexes, we investigated further catalytic systems for the desired transformation under mild conditions. Our specific focus was on phosphorus-free NNN-type pincer ligands, as they offer unique advantages such as being easily accessible and bench-stable. The precatalysts were synthesised *in situ* by reacting $MnBr(CO)_5$ with tridentate nitrogen ligands **L3**–**L11** (Scheme 9). Using 1-phenylethanol (**1a**) as the benchmark substrate, an initial screening was carried out using 0.5 mol% of metal precursor and chelating ligand, followed by the consecutive addition of 0.5 mol% NaO*t*Bu, substrate, and acetone.



Scheme 8. Ligand screening for the dehydrogenation of 1-phenylethanol.[a]

[a] Standard reaction conditions: 1-Phenylethanol **1a** (2 mmol), $MnBr(CO)_5$ (0.5 mol%), ligand (0.5 mol%), NaO*t*Bu (0.5 mol%), toluene (3 mL), acetone (1 mL), 90 °C, 2 h. Conversion and yield (in paranthesis) were determined by GC using hexadecane as an internal standard.

While the application of diethylentriamine (**L3**) as ligand resulted in a 71% yield of acetophenone (**2a**) under the selected reaction conditions, the methylated counterpart (**L4**)

and the *i*Pr-PyBOX ligand (**L5**) both failed and did not display any activity (Scheme 9). Inspired by the good performance of a manganese catalyst with a di-picolylamine ligand (**L6**, dpa) for transfer hydrogenation of ketones, we examined the activity of comparable catalytic systems with **L6** and related ligands (**L7**-**L9**), respectively.[64] Indeed, not only the combination of $MnBr(CO)_5$ and **L6** showed good activity, with 65% conversion and 61% yield of acetophenone (**2a**), but also *N*-methylated di-picolylamine (**L7**, Me-dpa) and tris-(2-picolyl)amine (**L8**, tpa) exhibited full conversion and yields up to 98%. Surprisingly, employing terpyridine (**L9**) as ligand with $MnBr(CO)_5$ gave no conversion at all. Under similar conditions, phosphorus containing pyridine-based ligands (**L10**, **L11**) revealed no formation of the product **2a** in the case of $MnBr(CO)_5$/**L10**, and a comparatively low yield of 33% by utilising $MnBr(CO)_5$/**L11**. To allow for a more precise comparison of **L7** and **L8**, we recorded a concentration-time graph applying $MnBr(CO)_5$ with each ligand. As displayed in Figure 9, the catalytic system with **L7** (blue graph) was found to provide superior activity in comparison to **L8** (red graph).

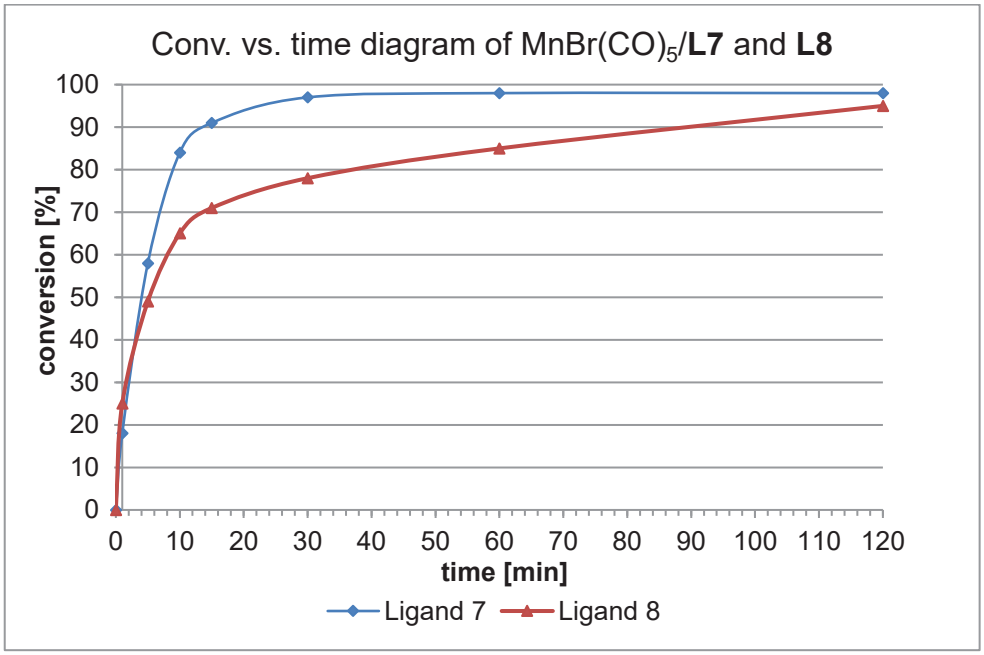


Figure 9. Conversion vs. time diagram for the dehydrogenation of 1-phenylethanol **1a** with $MnBr(CO)_5$ and ligand **L7** or **L8**.

Reaction conditions: 1-Phenylethanol **1a** (2 mmol), $MnBr(CO)_5$ (0.5 mol%), ligand (0.5 mol%), NaO*t*Bu (0.5 mol%), toluene (3 mL), acetone (1 mL), 90 °C. Conversion was determined by GC by using hexadecane as an internal standard.

A further comparison of different metal precursors revealed that the previously used $MnBr(CO)_5$ and ligand **L7** were the most active catalyst system for the attempted transformation (Figure 10). Interestingly, even noble-metal precursors based on ruthenium could not reach the attained high activity of this system.

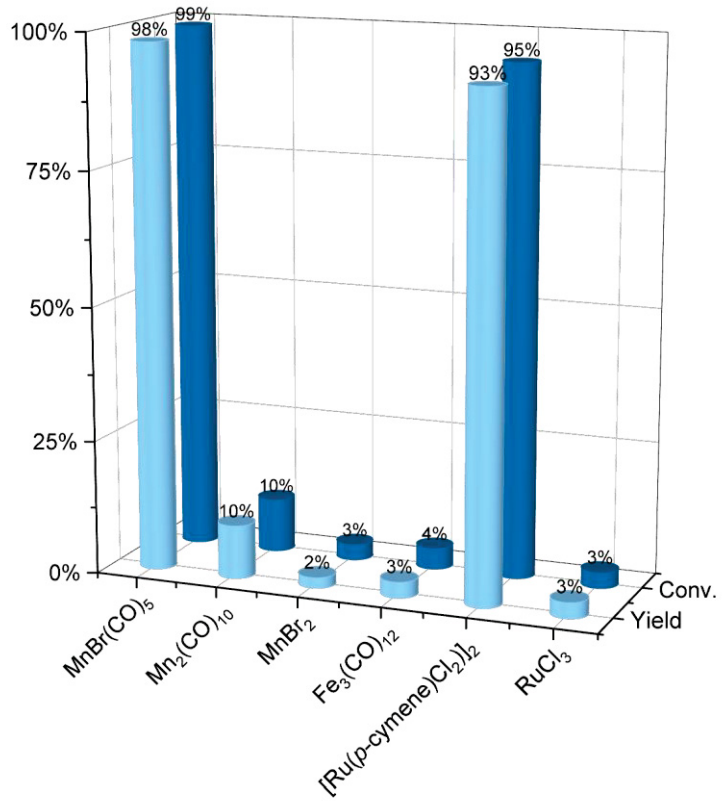


Figure 10. Metal precursor screening for the dehydrogenation of 1-phenylethanol.

Reaction conditions: 1-Phenylethanol **1a** (2 mmol), precursor (0.5 mol%), **L7** (0.5 mol%), NaO*t*Bu (0.5 mol%), toluene (3 mL), acetone (1 mL), 90 °C. Conversions were determined by GC by using hexadecane as an internal standard.

As previously expected, the addition of ligand **L7** to $MnBr(CO)_5$ is crucial for the obtained activity, irrespective of the presence or absence of an additional base (Table 3, Entries 1–2). If only the base was omitted, no catalytic activity was observed (Table 3, Entry 3). The ensuing optimisation of further reaction parameters showed that the preformation of the catalyst required 30 minutes, otherwise a lower yield was detected (Table 3, Entry 4). Further reduction of catalyst and base loading to 0.1 mol% caused a drop of activity, leading to only 22% yield (Table 3, Entry 5). Hence, we decided to utilise 0.5 mol% loading of precursor, ligand, and base in a 1:1:1 ratio to avoid an excess of base and the resulting aldol condensation, which leads to catalyst deactivation. The choice of solvent was determined by the reaction temperature of 90 °C, as lower temperatures led to not-reproducible results. Thus, only heptane and toluene, which have boiling points above this temperature were considered suitable for the reaction setup (Table 3, Entries 6–7). For this reason, acetone was always added shortly before the reaction vessel was closed. Conducting the reaction without acetone, resulted in a complete loss of activity and proved that acceptorless dehydrogenation does not take place under the prevailing conditions (Table 3, Entry 8).[32c,65] In summary, the initially

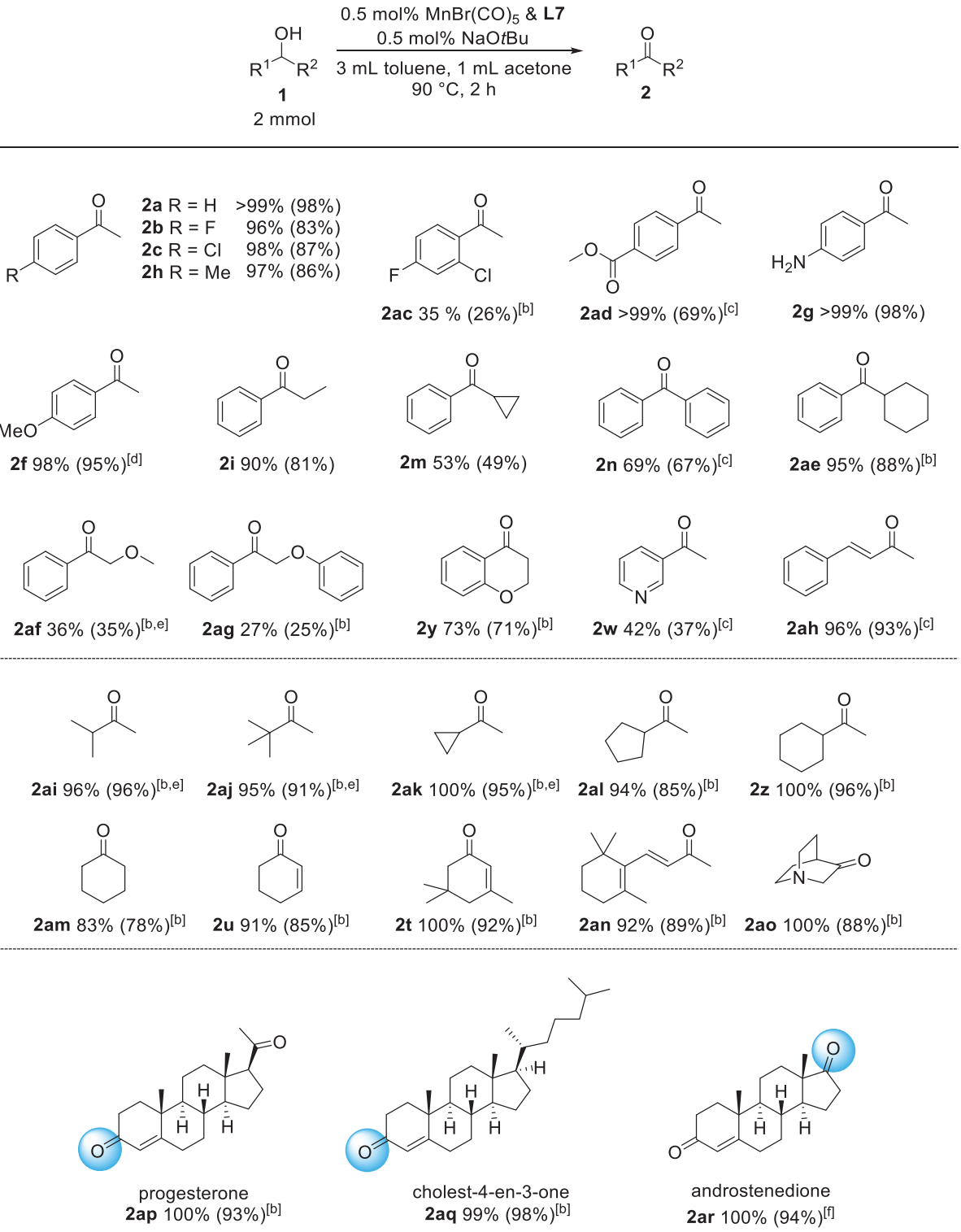
chosen reaction conditions of the ligand and precursor screening remained best, and full conversion of the benchmark substrate was accomplished after 2 h at 90 °C in toluene.

Table 3. Optimisation of the 1-phenylethanol dehydrogenation reaction conditions with $MnBr(CO)_5$ and **L7**.[a]

Entry	$MnBr(CO)_5$ [mol%]	Ligand [mol%]	Base [mol%]	Conv. [%]	Yield [%]
1	[0.5]	-	-	0	0
2	[0.5]	-	NaO*t*Bu [0.5]	0	0
3	[0.5]	**L7** [0.5]	-	0	0
4[b]	[0.5]	**L7** [0.5]	NaO*t*Bu [0.5]	94	93
5[c]	[0.1]	**L7** [0.1]	NaO*t*Bu [0.1]	24	22
6[d]	[0.5]	**L7** [0.5]	NaO*t*Bu [0.5]	92	90
7[e]	[0.5]	**L7** [0.5]	NaO*t*Bu [0.5]	98	96
8[f]	[0.5]	**L7** [0.5]	NaO*t*Bu [0.5]	0	0
9	[0.5]	**L7** [0.5]	NaO*t*Bu [0.5]	>99	98

[a] 1-Phenylethanol **1a** (2 mmol), 3 mL toluene, 1 mL acetone, 90 °C, 2 h. Conversion and yield were determined by GC using hexadecane as an internal standard. [b] 15 min formation time. [c] 1-Phenylethanol **1a** (4 mmol), $MnBr(CO)_5$ (0.1 mol%), **L7** (0.1 mol%), NaO*t*Bu (0.1 mol%). [d] 1 h reaction time, heptane (3 mL), acetone (1 mL). [e] 1 h reaction time. [f] Without acetone.

Next, we went on to test the general applicability of the catalytic system and subsequently deployed a variety of electronically diverse secondary alcohols to our methodology. *Para*-substituted acetophenone derivatives with electron-withdrawing or electron-donating groups were isolated in high yields ranging from 83% to 98% (Scheme 10, Entries **2a–c**, **2f–h**, **2ad**). On the contrary, application of *ortho*-chlorine substituted 1-(4-fluorophenyl)ethanol (**1ac**) resulted in a significantly lower catalyst activity, even with increased catalyst and base loading of 5 mol% and longer reaction times. However, the catalyst system showed good functional group tolerance as esters, amines, and methoxy ethers remained unaffected under our reaction conditions, and no competing side reactions were observed (**2ad**, **2g**, **2f**). Next, we examined the reactivity of several *β*-substituted derivatives. Substrates bearing ethyl (**1i**) or cyclopropyl groups (**1m**) decreased the catalytic activity of the system, yielding the desired ketones with 81% and 49%, respectively. When harsher conditions were used, congeners with bulkier moieties could be isolated in decent yields, furnishing 67% benzophenone (**2n**) and 88% cyclohexylphenyl ketone (**2ae**). Methoxy- or phenoxy-substitutents in the *β*-position were well tolerated, however, lower yields were detected (**2af–2ag**).

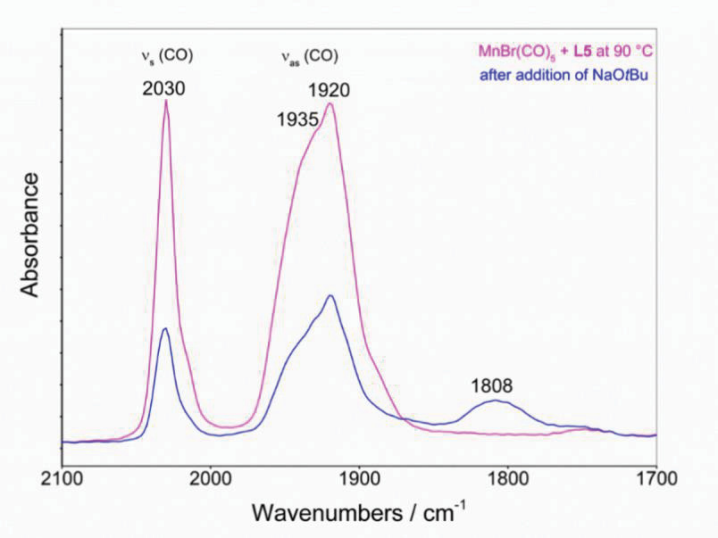


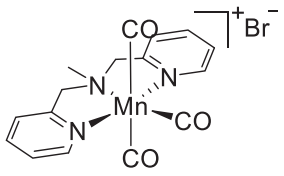
Scheme 9. Substrate scope for the dehydrogenation of secondary alcohols using $MnBr(CO)_5$ and **L7**.[a]

Conversions were determined by GC using hexadecane as an internal standard. Isolated yields are given in parentheses. [a] Reaction conditions: substrate (2 mmol), $MnBr(CO)_5$ (0.5 mol%), **L7** (0.05 mol%), NaO*t*Bu (0.5 mol%), toluene (3 mL), acetone (1 mL), 90 °C, 2 h. [b] Reaction conditions: Substrate (1 mmol), $MnBr(CO)_5$ (5 mol%), **L7** (5 mol%), NaO*t*Bu (5 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. [c] Reaction conditions: Substrate (1 mmol), $MnBr(CO)_5$ (1 mol%), **L7** (1 mol%), NaO*t*Bu (1 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. [d] NaOMe instead of NaO*t*Bu. [e] GC yield. [f] 48 h reaction time.

Furthermore, it could be demonstrated that heteroaromatic substrates (**1y**,**1w**) as well as *α*,*β*-unsaturated alcohols (**1u**) were effectively dehydrogenated. 4-Chromanone (**2y**) and 3-acetylpyridine (**2w**) were isolated in 71% and 37%, respectively. Moreover, 4-phenyl-3-buten-2-one was isolated in near quantitative yield without observing any side reactions (**2ah**). In addition, the reactivity of the new catalytic system was examined for the dehydrogenation of acyclic and cyclic aliphatic secondary alcohols. Fortunately, all respective substrates were successfully dehydrogenated, albeit 5 mol% catalyst and base loading were shown to be necessary to yield the desired products in good to excellent yields after 24 h. An increase in ring size of cyclic alcohols had no significant influence on the activity of the catalytic system (**2ak–2al**, **2z**). It could be demonstrated that cyclohexanol (**1am**) and structurally related compounds (**1u–1t**) were dehydrogenated in good yields (78–92%) to the corresponding ketones. Notably, the oxidation of 2-cyclohexenol (**1u**), which can act as Michael acceptor as reported *vide supra* in chapter 6.1, was accomplished without any detectable side products. In the case of allylic substrate **1an**, a conversion of 92% was observed yielding 89% *β*-ionone (**2an**), which is widely applied in the fragrance industry. Likewise, full conversion of quinuclidine-3-ol (**1ao**) was attained, furnishing 88% of the desired ketone (**2ao**). To further probe the general applicability of the methodology toward bio-active compounds, we attempted the dehydrogenation of natural steroids bearing secondary alcohol moieties. To our delight, 3*β*-hydroxypregn-5-en-20-on (**1ap**) and cholest-5-en-3*β*-ol (**1aq**) were fully dehydrogenated using 5 mol% $MnBr(CO)_5$, 5 mol% **L7**, and 5 mol% NaO*t*Bu at 90 °C. In both cases the desired product was isolated in near quantitative yield after 24 h. Notably, a selective isomerisation of the double bond (>99%) was obtained to yield the more stable enone products (**2ap–2aq**). Similarly, testosterone (**1ar**) was successfully oxidised to androstenedione (**2ar**) after 48 h, and an excellent isolated yield of 94% was achieved.

To probe the formation of the precatalyst and the catalytically active species, we tested the isolated complex $[Mn(Me\text{-}dpa)(CO)_3]Br$ (**Mn-9**) in the initially conducted dehydrogenation of 1-phenylethanol (**1a**) and observed a similar activity compared to the *in situ* formed catalyst. Characteristic CO bands at 2030, 1935, and 1920 cm^{-1} during *in situ* IR spectroscopic investigations proved the *in situ* generated species to be precatalyst **Mn-9** (Figure 11). The intensities of the carbonyl bands increased with higher temperature owing to the improved solubility of the complex. After addition of NaO*t*Bu a gradual decrease of the CO bands was observed and a new band at 1808 cm^{-1} appeared. From this data, we inferred that a new catalyst species was formed. However, characterisation of this active intermediate proved to be difficult, due to its instability.



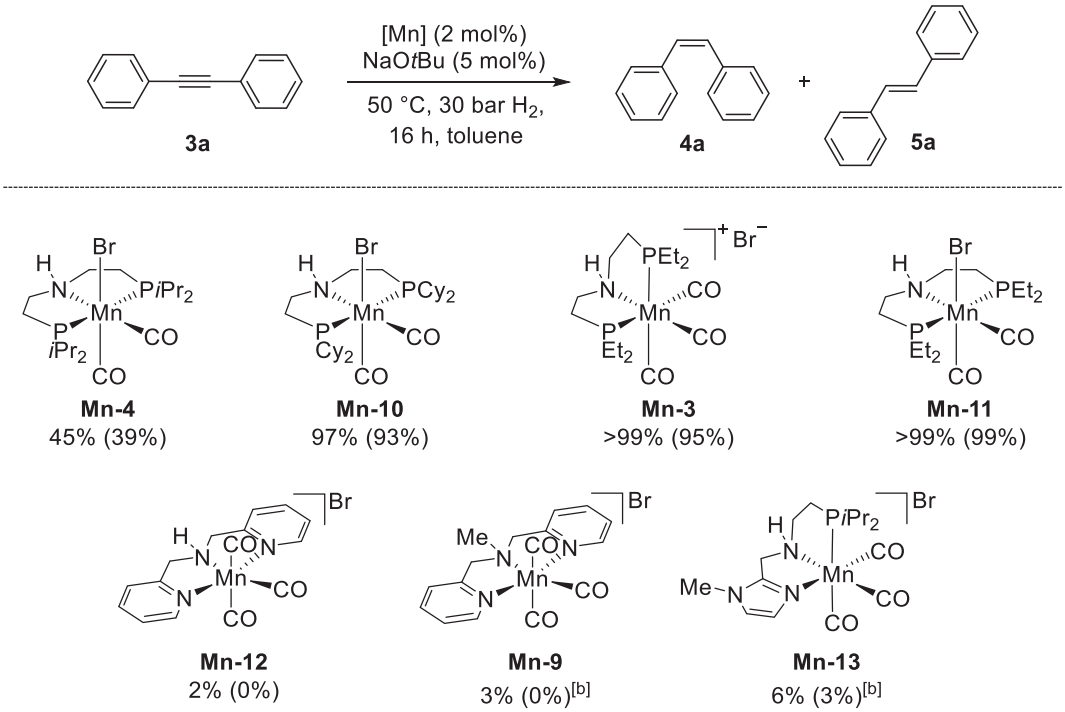


Mn-9

Figure 11. *In situ* IR spectrum of $MnBr(CO)_5$ and **L7** in heptane.

6.3 Chemoselective Semihydrogenation of Alkynes Catalysed by Manganese(I)-PNP Pincer Complexes

As described in the introduction, reports on non-noble metal pincer complexes for the semihydrogenation of alkynes are scarce. In particular, manganese based catalysts were not studied for the stereoselective hydrogenation of alkynes to alkenes with molecular hydrogen until recently. Hence, in search for a practical catalytic system, the potential of manganese based pincer complexes, which were previously developed in our laboratories, was evaluated for the semihydrogenation of 1,2-diphenylethyne **3a** (Scheme 11).



Scheme 10. The tested manganese complexes for the hydrogenation of 1,2-diphenylethyne **3a**.[a]

[a] General reaction conditions: 0.5 mmol substrate **3a**, 2 mol% [Mn], 5 mol% NaO*t*Bu, 1 mL toluene, *Z*/*E:* >99. [b] 5 mol% KO*t*Bu, 1 mL heptane, *Z*/*E:* n.d..

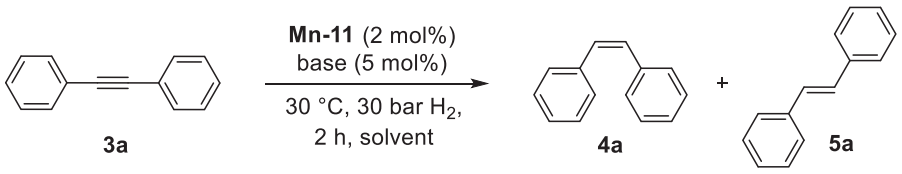
Using 2 mol% catalyst and 5 mol% base loading at 30 bar H_2 and 50 °C, complexes **Mn-12** and **Mn-9** were not active for this hydrogenation. Whereas **Mn-10**, **Mn-3** and **Mn-11** showed high activity and performed equally well. Full conversion was observed in all cases, exclusively furnishing the *Z*-isomer (**4a**) in high yields (93–99%). Complexes **Mn-4** and **Mn-13** displayed inferior catalytic activities with 39% and 3% yield, respectively. A further comparison at a shorter reaction time of 5 h showed **Mn-11** to be the most active catalyst for the attempted transformation (Table 4, Entries 1–3). As full conversion was still obtained after lowering the reaction time to 2 h, we reduced the temperature to 30 °C (Table 4, Entries 4–5).

Table 4. Optimisation of the 1,2-diphenylacetylene hydrogenation reaction conditions.[a]

Entry	Catalyst	Catalyst loading [mol%]	T [°C]	p [bar]	t [h]	Conv. [%]	Yield [%]	*Z*/*E*
1	**Mn-10**	2	50	30	5	61	59	97:3
2[b]	**Mn-3**	2	50	30	5	60	56	97:3
3	**Mn-11**	2	50	30	5	>99	99	99:1
4	**Mn-11**	2	50	30	2	>99	99	>99
5	**Mn-11**	2	30	30	2	73	67	>99
6[b]	**Mn-11**	1	30	30	4	>99	99	>99
7[b]	**Mn-11**	0.5	30	30	4	77	74	>99
8[b]	**Mn-11**	1	30	5	4	92	88	>99

[a] General reaction conditions: 0.5 mmol substrate **3a**, 0.5-2 mol% [Mn], 5 mol% NaO*t*Bu, 1 mL toluene. Conversions were determined by GC using hexadecane as an internal standard. Isolated yields. *Z*/*E* ratio determined by NMR analysis. [b] 0.5 mmol substrate **3a**, 0.5-2 mol% [Mn], 5 mol% KO*t*Bu, 1 mL heptane.

Table 5. Screening of solvent and bases for the hydrogenation of 1,2-diphenylacetylene.[a]



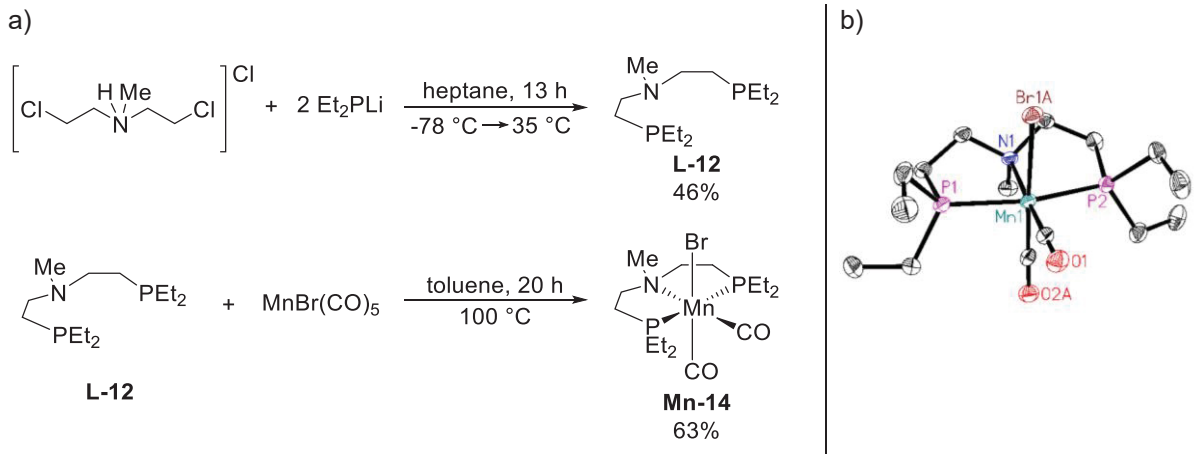
Entry	Mn-11 [mol%]	Solvent	Base	Conv. [%]	Yield [%]	*Z*/*E*
1	2	CH_2Cl_2	KO*t*Bu	25	21	97:3
2	2	Et_2O	KO*t*Bu	53	51	99:1
3	2	THF	KO*t*Bu	19	17	97:3
4	2	dioxane	KO*t*Bu	26	23	97:3
5	*2*	*t*-AmylOH	KO*t*Bu	5	0	---
6	2	EtOH	KO*t*Bu	0	---	---
7	2	toluene	KO*t*Bu	90	89	>99
8	2	heptane	KO*t*Bu	>99	>99	>99
9	1	heptane	NaO*t*Bu	88	86	>99
10	1	heptane	KOH	8	4	n.d.
11	1	heptane	KO*t*Bu	99	98	>99
12	-	heptane	KO*t*Bu	0	---	---

[a] General reaction conditions: 0.5 mmol substrate **3a**, 1-2 mol% **Mn-11**, 5 mol% base, 30 °C, 30 bar H_2, 2 h, 1 mL solvent. Conversions were determined by GC using hexadecane as an internal standard. Isolated yields. *Z*/*E* ratio determined by NMR analysis.

Notably, reduction of the catalyst loading revealed that complex **Mn-11** retained high activity, albeit 0.5 or 1 mol% catalyst loading was used (Table 4, Entries 6–8).

Subsequent optimisation of solvent and base revealed that the best activity was obtained, when KO*t*Bu was used as base and the reaction was conducted in heptane (Table 5, Entries 8 & 11). As expected, a control experiment without any catalyst present in the reaction, exhibited no catalytic activity (Table 5, Entry 12).

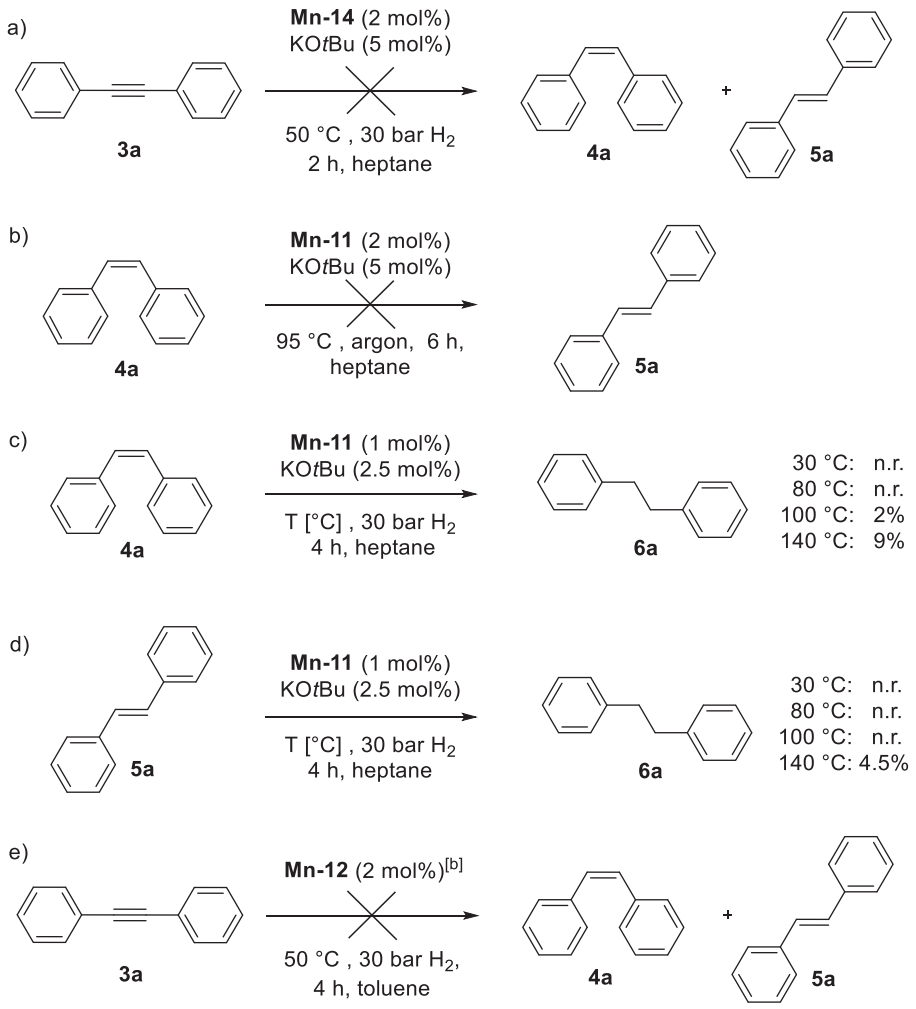
Since pincer complexes are frequently expected to proceed through an outer-sphere mechanism by incorporation of the pincer ligand during the bond activation (MLC, see chapter 3), we synthesised the *N*-methylated pincer complex **Mn-14**, in order to distinguish between inner- or outer-sphere mechanism.[66] Therefore, we first synthesised *N*-methyl *bis*(2-diethylphosphinoethyl)amine, starting from *N*-methyl *bis*(2-chloroethyl)amine hydrochloride.[67] Lithiation with Et_2PLi yielded ligand **L-12** in 46% (Scheme 12, a). Next, the ligand was reacted with $MnBr(CO)_5$ in toluene and complex **Mn-14** was obtained in 63% yield. Crystals suitable for X-ray analysis were grown from a saturated solution of **Mn-14** in methanol at 0 °C (Scheme 12, b).



Scheme 11. a) Synthesis of *N*-methylated manganese PNP complex **Mn-14**. b) Molecular structure of **Mn-14** in the solid state. Thermal ellipsoids are drawn at 30% probability. Hydrogen atoms and atoms of lower occupancy are omitted for clarity.

Blocking the active *N*-H site of a ligand backbone with a methyl group prevents any reaction, which proceeds *via* an outer-sphere mechanism. Using **Mn-14** for the model reaction with 1,2-diphenylethyne **3a** resulted in a complete loss of activity (Scheme 13, a). Hence, we concluded that the hydrogenation by **Mn-14** follows an outer-sphere mechanism, involving the *N*-H moiety of the ligand. This assumption was further supported by DFT computations. Moreover, an

outer-sphere mechanism was reported in previous works regarding the hydrogenation of esters, nitriles, ketones, and aldehydes using manganese based PNP pincer catalysts.[22e,,68]



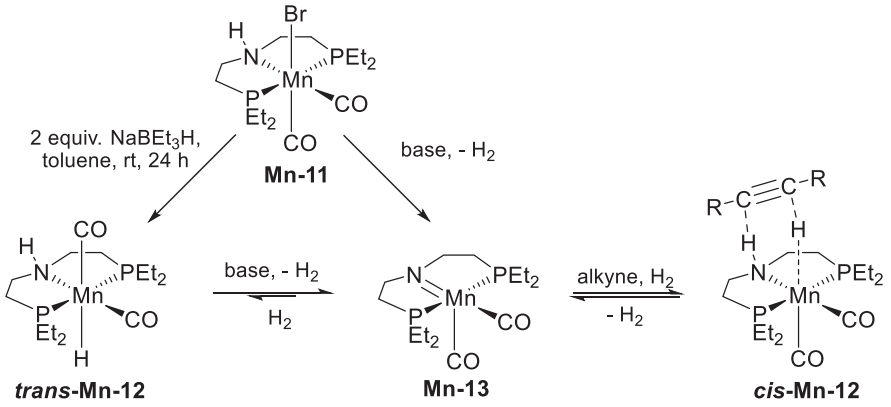
Scheme 12. Mechanistic experiments for the semihydrogenation of alkynes.[a]

[a] General reaction conditions: 0.5 mmol substrate **3a**, 1 mL toluene, *Z*/*E:* >99. Conversions were determined by GC using hexadecane as an internal standard. *Z/E* ratio determined by NMR analysis. [b] In the presence of 5 mol% KO*t*Bu: 85% conv. and 85% yield.

Next, we were interested in the potential isomerisation ability of our developed catalyst system. In order to test this capability, *Z*-stilbene (**4a**) was heated with 2 mol% **Mn-11** at 95 °C for 6 h without dihydrogen. In contrast to the iron PNP complex **Fe-4** previously reported by Milstein and co-workers, *E*-stilbene (**5a**) was not formed under our reaction conditions (Scheme 13, b).[55] Moreover, no isomerisation was observed in the presence of 30 bar hydrogen, even when increased reaction temperatures were applied (Scheme 13, c). It is noteworthy that during this reaction setup, 1,2-diphenylethane **3a** is only formed to a small extent in the case of *Z*-stilbene (**4a**), as well as *E*-stilbene (**5a**) (Scheme 13, c–d). At elevated temperature (140 °C) presumably most of the heptane and stilbene are in the gas phase, resulting in a high

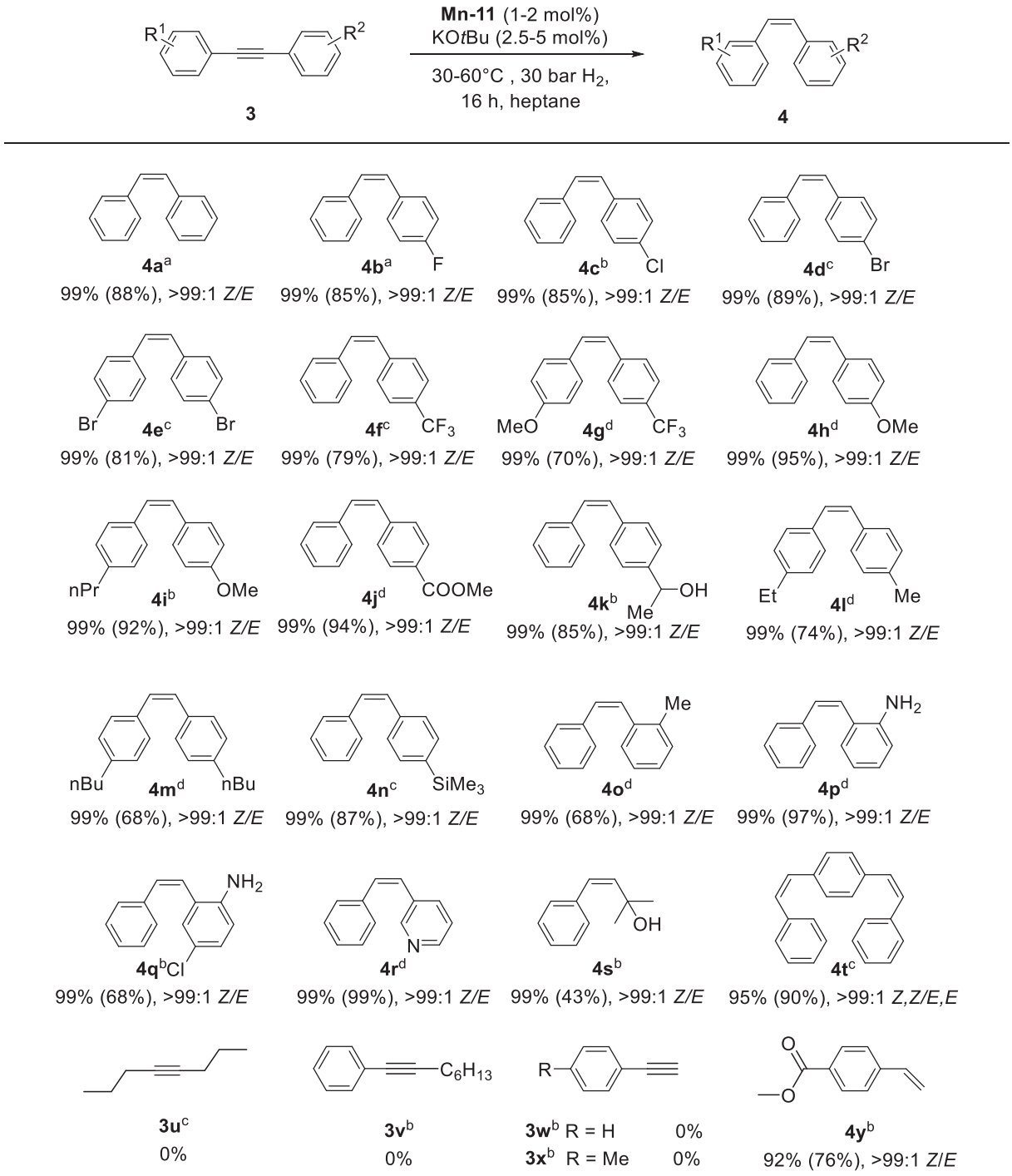
catalyst loading in the liquid phase. However, it could be demonstrated that the hydrogenation of the triple bond occurs over the reduction of the double bond with catalyst **Mn-11** under the described conditions.

Moreover, we investigated the active catalyst species by treating **Mn-11** with 2 equiv of $NaBEt_3H$ (1 M in THF) for 24 h at room temperature. We observed formation of a mixture of *trans*-**Mn-12** and *cis*-**Mn-12**, which was confirmed by ^1H NMR analysis. For the following reactions, the catalyst was handled as a stock solution, because of its instability in pure form. Interestingly, using 2 mol% of hydride complex **Mn-12** in the model reaction did not provide comparable results to the use of **Mn-11** and a perceptibly lower yield of 85% *Z*-stilbene (**4a**) was observed (Scheme 13, e). It is important to note that the hydrogenation did not take place without base, indicating the involvement of base in the rate-limiting reaction step. A possible explanation of this catalytic behaviour is the predominant formation of the thermodynamically more stable *trans*-**Mn-12**, which was verified by NMR analysis and DFT computations. In the case of the *trans*-isomer the concerted hydride transfer from the catalyst to the substrate *via* the proposed outer-sphere mechanism cannot take place. Consequently, the base is needed to form the amido complex **Mn-13** as an intermediate, which reacts to *cis*-**Mn-12** under hydrogen atmosphere. Then the resulting *cis*-**Mn-12** undergoes a concerted hydride transfer with the alkyne (Scheme 14).



Scheme 13. Postulated formation of *trans*- and *cis*-**Mn-12**.

To further elucidate the applicability of our developed catalytic system, a variety of functionalised alkynes were applied as substrates under the optimised reaction conditions (Scheme 15). Herein, internal alkynes bearing halide substituents such as fluorine (**3b**), chlorine (**3c**), bromine (**3d**–**e**) or trifluoromethyl (**3f**–**g**) in *para*-position were well-tolerated and high yields of the desired *Z*-alkenes were obtained (70–89%). Likewise, methoxy (**4h, 4i**) and ester (**4j**) substituted alkynes were selectively reduced with full conversion and excellent yields of up to 95%.



Scheme 14. Substrate scope for the semihydrogenation of alkynes using **Mn-11.**

Conversions were determined by GC using hexadecane as an internal standard. Isolated yields are given in parentheses. [a] 1 mol% **Mn-11**, 2.5 mol% KO*t*Bu, 5 bar H_2, 30 °C, 4 h. [b] 2 mol% **Mn-11**, 5 mol% KO*t*Bu, 30 bar H_2, 60 °C, 16 h. [c] 1 mol% **Mn-11**, 2.5 mol% KO*t*Bu, 30 bar H_2, 60 °C, 16 h. [d] 2 mol% **Mn-11**, 5 mol% KO*t*Bu, 30 bar H_2, 30 °C, 16 h.

In the case of sensitive functional substituents such as keto groups (**4k**), a preferential hydrogenation of the carbonyl group was detected, even though milder conditions of 1 mol% **Mn-11** at 30 °C were chosen. Applying optimised conditions, both functionalities were

hydrogenated, giving access to the corresponding (*Z*)-1-(4-styrylphenyl)ethan-1-ol (**4k**) in 85% isolated yield. Moreover, alkynes with alkyl moieties (**3l**, **3m**) or a trimethylsilyl group (**3n**) in *para*-position posed no issues and were successfully reduced in good yields. Similarly, *ortho*-substituted alkynes (**3o**–**q**) were fully converted to the desired alkenes with yields ranging from 68% to 97%. Examplarily for heteroaromatic alkynes, the semihydrogenation for 3-(phenylethynyl) pyridine (**3r**) proceeded selectively to the *Z*-olefin **4r** in quantitative yield. Furthermore, substrate **3s** carrying an aromatic and aliphatic moiety was hydrogenated to the corresponding alkene (**4s**) in a moderate yield (43%). Next, the diyne **3t** was efficiently reduced at both triple bonds yielding the synthetically relevant 1,4-di((*Z*)-styryl) benzene (**4t**) in 90% yield. Subsequently, the hydrogenation of the more challenging internal aliphatic alkynes (**3u**, **3v**) was tested, leading to no conversion even under harsher reaction conditions. Finally, the versatility of the catalytic system was further probed for terminal alkynes. Here, only the terminal alkyne **3y** activated by a methylester moiety was successfully hydrogenated to 4-vinyl methylbenzoate (**4y**) in 76% isolated yield.

7 Summary and Outlook

The aim of the present work was the examination of iron- and manganese-based non-noble pincer complexes and their application towards industrially relevant transformations. This included the screening of different pincer complexes and the investigation of their potential as catalysts for the homogeneous dehydrogenation reactions of alcohols, as well as the semihydrogenation of alkynes.

In detail, we investigated the catalytic activity of an iron PNP pincer complex (**Fe-1**) in the transfer dehydrogenation of different alcohols. The applied catalyst efficiently accelerates the transformation of secondary alcohols to ketones in the presence of acetone as hydrogen acceptor. Moreover, milder reaction conditions compared to most known acceptorless dehydrogenations were attained. The mechanism of the catalytic oxidation by **Fe-1** was studied in detail by means of DFT studies, which provided information regarding the role of the hydrogen acceptor.

In addition, a manganese-based catalyst system with a phosphorus-free NNN-type pincer ligand was developed for the same transformation. The precatalyst **Mn-9** was conveniently synthesised *in situ* by reacting $MnBr(CO)_5$ with the phosphorus-free NNN pincer ligand (**L-7**). In this way, aromatic and aliphatic alcohols were smoothly oxidised to the corresponding ketones even with low catalyst and base loading.

In the future, sustainability will become more of a focus for chemical processes, especially regarding the scarcity of resources and rising prices for conventional chemical precursors produced from fossil fuels. The catalytic dehydrogenation of biosourced alcohols as a pathway to valuable ketones could be an alternative source of supply if the cost of the process can compete with the conventional production. Therefore, we are in need of practical catalytic systems which are capable of efficiently oxidising alcohols. In this respect, the catalysts themselves should rely on non-noble metals, and it is apparent that the cost of the ligand will also play an important role. Therefore, future studies should deal with less sophisticated ligands such as phosphorus-free alternatives, which simplify the handling and production of the corresponding catalysts and will consequently be advantageous with respect to the cost of preparation. Additionally, a future challenge will be the enhancement of substrates to more complex alcohols, which are more challenging.

Besides the described dehydrogenation reactions, we focused on the catalytic semihydrogenation of alkynes in the presence of molecular hydrogen. For this purpose, manganese-based pincer complexes were compared to assess their catalytic activity. Notably, catalyst **Mn-11** is a particularly efficient catalyst for the highly chemo- and stereoselective

semihydrogenation of internal alkynes to the corresponding *Z*-alkenes. Mechanistic investigations based on DFT calculations, as well as control experiments, revealed that the hydrogenation proceeds *via* an outer-sphere mechanism with a direct involvement of the pincer ligand.

Olefins are important building blocks for fine and bulk chemistry and *Z*-alkenes are often an inherent part of pharmaceutically active compounds. Hence, a convenient, selective reduction is in demand, and pincer catalysts can play an important role in achieving this. Moreover, especially for the production of pharmaceuticals, noble metal traces need to be kept below a low threshold, and consequently precious metal catalysts should be replaced by non-noble pincer complexes.[69] Therefore, it is worthwhile to pursue research into non-noble pincer catalysts and further develop simplified ligand systems to ensure increased attractiveness for industrial applications.

8 References

[1] A. Behr and P. Neubert, *Applied Homogeneous Catalysis*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, **2012**.

[2] C. M. Moore, N. K. Szymczak in *Pincer and Pincer-Type Complexes: Applications in Organic Synthesis and Catalysis* (Ed.: K. J. Szabó, O. F. Wendt), VCH, Weinheim, **2014**.

[3] J. W. Morgan, E. Anders, Proc. Natl. Acad. Sci. *U. S. A.* **1980**, *77*, 6973–6977.

[4] a) D. L. Anderson, *Theory of the Earth*, Blackwell Science Ltd, Boston, **1990**; b) W. M. Haynes, D. R. Lide, T. J. Bruno, *CRC Handbook of Chemistry and Physics*, Taylor & Francis Group, LLC, Boca Raton, **2017**.

[5] S. Jankovic, *Wirtschaftsgeologie der Erze*, Springer-Verlag, Vienna, **2013**.

[6] P. Cloud, *Econ. Geol.* **1973**, *68*, 1135–1143.

[7] K. Schröder, K. Junge, B. Bitterlich, M. Beller in *Iron Catalysis* (Ed.: Bernd Plietker), Springer Verlag, Berlin Heidelberg, **2011**. pp. 83–84.

[8] W. Ternes, *Biochemie der Elemente: Anorganische Chemie biologischer Prozesse*, Springer Verlag, Berlin Heidelberg, **2013**.

[9] K. W. Kolasinski, *Surface Science: Foundations of Catalysis and Nanoscience,* Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, **2012**.

[10] A. Fürstner, *ACS Cent. Sci.* **2016**, *2*, 778–789.

[11] A. F. Holleman, E. Wiberg, N. Wiberg, *Lehrbuch der Anorganischen Chemie*, Walter de Gruiter Verlag, Berlin, **2007**.

[12] W. Zhang, C. Y. Cheng, *Hydrometallurgy* **2007**, *89*, 137–159.

[13] L. A. Graham, A. R. Fout, K. R. Kuehne, J. L. White, B. Mookherji, F. M. Marks, G. P. A. Yap, L. N. Zakharov, A. L. Rheingold, D. Rabinovich, *Dalton Trans.* **2005**, *1*, 171–180.

[14] N. A. Law, M. T. Caudle, V. L. Pecoraro, *Adv. Inorg. Chem.* **1998**, *46*, 305–440.

[15] A. W. Rutherford, P. Faller, *Philos. Trans. R. Soc., B* **2003**, *358*, 245–253.

[16] M. Beller, A. Renken, R. A. van Santen, *Catalysis: From Principles to Applications*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, **2012**.

[17] W. Zhang, J. L. Loebach, S. R. Wilson, E. N. Jacobsen, *J. Am. Chem. Soc.* **1990**, *112*, 2801–2803.

[18] L. Lloyd, *Fundamental and Applied Catalysis – Handbook of Industrial Catalysts*, Springer Science+Business Media, LLC, New York, **2011**.

[19] The corresponding data can be found at the "*U.S. Geological Survey*" website: https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Produkte/produkte_node.html?tab=RohstoffRohsto. Visited on 18.02.2021.

[20] The corresponding data can be found at: https://tradingeconomics.com/commodity. Visited on 18.02.2021.

[21] M. Albrecht, G. van Koten, *Angew. Chem. Int. Ed.* **2001**, *40*, 3750–3781.

[22] a) G. R. Fulmer, W. Kaminsky, R. A. Kemp, K. I. Goldberg, *Organometallics* **2011**, *30*, 1627–1636; b) M. Gargir, Y. Ben-David, G. Leitus, Y. Diskin-Posner, L. J. W. Shimon, D. Milstein, *Organometallics* **2012**, *31*, 6207–6214; c) K. Riener, M. J. Bitzer, A. Pöthig, A. Raba, M. Cokoja, W. A. Herrmann, F. E. Kühn, *Inorg. Chem.* **2014**, *53*, 12767–12777; d) A. G. Nair, R. T. McBurney, D. B. Walker, M. J. Page, M. R. D. Gatus, M. Bhadbhade, B. A. Messerle, *Dalton Trans.* **2016**, *45*, 14335–14342; e) S. Elangovan, M. Garbe, H. Jiao, A. Spannenberg, K. Junge, M. Beller, *Angew. Chem. Int. Ed.* **2016**, *55*, 15364–15368.

[23] T. Ikariya, M. Shibasaki, *Bifunctional Molecular Catalysis*, Springer, Berlin, **2011**.

[24] a) J. Zhang, G. Leitus, Y. Ben-David, D. Milstein, *Angew. Chem. Int. Ed.* **2006**, *45*, 1113–1115; b) T. Zell, D. Milstein, *Acc. Chem. Res.* **2015**, *48*, 1979–1994.

[25] a) J. R. Khusnutdinova, D. Milstein, *Angew. Chem. Int. Ed.* **2015**, *54*,12236–12273; b) P. A. Dub, N. J. Henson, R. L. Martin, J. C. Gordon, *J. Am. Chem. Soc.* **2014**, *136*, 3505–3521; c) L. Alig, M. Fritz, S. Schneider, *Chem. Rev.* **2019**, *119*, 4, 2681–2751.

[26] a) S. Werkmeister, H. Junge, B. Wendt, E. A. Alberico, H. Jiao, W. Baumann, K. Junge, F. Gallou, M. Beller, *Angew. Chem. Int. Ed*. **2014**, *53*, 8722–8726; *Angew. Chem.* **2014**, *126*, 8867–8871. b) C. Bornschein, S. Werkmeister, B. Wendt, H. Jiao, E. A. Alberico, H. Junge, K. Junge, M. Beller, *Nat. Commun*. **2014**, *5*, 4111–4122; c) S. Elangovan, B. Wendt, C. Topf, S. Bachmann, M. Scalone, A. Spannenberg, H. Jiao, W. Baumann, K. Junge, M. Beller, *Adv. Synth. Catal*. **2016**, *358*, 820–825; d) R. Huber, A. Passera, A. Mezzetti, *Organometallics* **2018**, *37*, 396–405; e) W. Zhou, Z. Wei, A. Spannenberg, H. Jiao, K. Junge, H. Junge, M. Beller, *Chem. - Eur. J.* **2019**, *25*, 8459–8464; f) L. Zhang, Y. Tang, Z. Han, K. Ding, *Angew. Chem. Int. Ed.* **2019**, *58*,4973–4977; g) J. Hu, Q. J. Bruch, A. J. M. Miller, *J. Am. Chem. Soc.* **2021**, *143*, 945–954.

[27] a) P. M. Fanara, S. N. MacMillan, D. C. Lacy, *Organometallics* **2020**, *39*, 3628–3644.

[28] L. Piccirilli, D. L. J. Pinheiro, M. Nielsen, *Catalysts* **2020**, *10*, 1–116.

[29] a) N. Gorgas, K. Kirchner, *Acc. Chem. Res.* **2018**, *51*, 1558–1569; b) F. Kallmeier, R. Kempe, *Angew. Chem. Int. Ed.* **2018**, *57*, 46–60; c) T. Zell, R. Langer, *ChemCatChem* **2018**, *10*, 1930–1940; d) D. Wei, C. Darcel, *Chem. Rev.* **2019**, *119*, 4, 2550–2610.

[30] I. W. C. E. Arends, R. A. Sheldon in *Modern Oxidation Methods*, *Vol. 2* (Ed.: J.-E. Bäckvall), Wiley-VCH, Weinheim, **2010**, pp.147–180.

[31] A. V. Polukeev, P. V. Petrovskii, A. S. Peregudov, M. G. Ezernitskaya, A. A. Koridze, *Organometallics* **2013**, *32*, 1000–1015.

[32] a) G. E. Dobereiner, R. H. Crabtree, *Chem. Rev.* **2010,** *110*, 681–703; b) S. Werkmeister, J. Neumann, K. Junge, M. Beller, *Chem. Eur. J.* **2015**, *21*, 12226–12250; c) R. H. Crabtree, *Chem. Rev.* **2017**, *117*, 9228–9246; d) G. A. Filonenko, R. van Putten, E. J. M. Hensen, E. A. Pidko, *Chem. Soc. Rev*. **2018**, *47*, 1459–1483; d) H. Valdés, M. A. García-Eleno, D. Canseco-Gonzalez, D. Morales-Morales, *ChemCatChem* **2018**, *10*, 3136–3172.

[33] C. F. de Graauw, J. A. Peters, H. van Bekkum, J. Huskens, *Synthesis* **1994**, 1007–1017.

[34] a) D. Morales-Morales, R. Redón, Z. Wang, D. W. Lee, C. Yung, K. Magnuson, C. M. Jensen, *Can. J. Chem.* **2001**, *79*, 823–829; b) R. Levy, C. Azerraf, D. Gelman, K. Rueck-Braun, P. N. Kapoor, *Catal. Commun.* **2009**, *11*, 298–301; c) Y. Shi, T. Suguri, S. Kojima, Y. Yamamoto, *J. Organomet. Chem.* **2015**, *799-800*, 7–12.

[35] D. H. Nguyen, Y. Morin, L. Zhang, X. Trivelli, F. Capet, S. Paul, S. Desset, F. Dumeignil, R. M. Gauvin, *ChemCatChem* **2017**, *9*, 2652–2660.

[36] a) G. Zhang, S. K. Hanson, *Org. Lett.* **2013**, *15*, 650–653; b) G. Zhang, K. V. Vasudevan, B. L. Scott, S. K. Hanson, *J. Am. Chem. Soc.* **2013**, *135*, 8668–8681.

[37] S. Chakraborty, P. O. Lagaditis, M. Förster, E. A. Bielinski, N. Hazari, M. C. Holthausen, W. D. Jones, S. Schneider, *ACS Catal.* **2014**, *4*, 3994–4003.

[38] A. Bruneau-Voisine, D. Wang, T. Roisnel, C. Darcel, J.-B. Sortais, *Catal. Commun.* **2017**, *92*, 1–4.

[39] Z. Dai, Q. Luo, H. Jiang, Q. Luo, H. Li, J. Zhang, T. Peng, *Catal. Sci. Technol.* **2017**, *7*, 2506–2511.

[40] a) C. O. Tuck, E. Perez, I. T. Horvath, R. A. Sheldon, M. Poliakoff, *Science* **2012**, *337*, 695–699; b) M. Trincado, D. Banerjee, H. Grützmacher, *Energy Environ. Sci.* **2014**, *7*, 2464–2503.

[41] K. Sordakis, C. Tang, L. K. Vogt, H. Junge, P. J. Dyson, M. Beller, G. Laurenczy, *Chem. Rev.* **2018**, *118*, 372–433.

[42] a) S. Budweg, K. Junge and M. Beller*, Catal. Sci. Technol.* **2020**, *10*, 3825–3842; b) C. Guan, Y. Pan, T. Zhang, M. J. Ajitha, K.-W. Huang, Chem Asian J. 2020, 15, 937–946.

[43] E. Alberico, P. Sponholz, C. Cordes, M. Nielsen, H.-J. Drexler, W. Baumann, H. Junge, M. Beller, *Angew. Chem. Int. Ed.* **2013**, *52*, 14162–14166.

[44] E. A. Bielinski, M. Förster, Y. Zhang, W. H. Bernskoetter, N. Hazari, M. C. Holthausen, *ACS Catal.* **2015**, *5*, 2404–2415.

[45] M. Andérez-Fernández, L. K. Vogt, S. Fischer, W. Zhou, H. Jiao, M. Garbe, S. Elangovan, K. Junge, H. Junge, R. Ludwig, M. Beller, *Angew. Chem. Int. Ed.* **2017**, *56*, 559–562.

[46] a) A. Cirla, J. Mann, *Nat. Prod. Rep.* **2003**, *20*, 558–564; b) D. J. Ager in *Handbook for Homogeneous Hydrogenation* (Ed.: J. G. de Vries and C. J. Elsevier), Wiley-VCH, Weinheim, **2007**, p. 745.

[47] a) P. N. Rylander in *Catalytic Hydrogenation in Organic Syntheses*, Academic Press, New York, **1979**; b) P. G. Andersson, I. J. Munslow in *Modern Reduction Methods*, Wiley, New York, **2008**; c) C. Oger, L. Balas, T. Durand, J.-M. Galano, *Chem. Rev.* **2013**, *113*, 1313–1350.

[48] a) H. Lindlar, *Helv. Chim. Acta* **1952**, *35*, 446–450; b) H. Lindlar, R. Dubuis, *Org. Synth.* **1966**, *46*, 89.

[49] R. Chinchilla, C. Najera, *Chem. Rev.* **2014**, *114*, 1783–1826.

[50] a) S. Fu, N.-Y. Chen, X. Liu, Z. Shao, S. P. Luo and Q. Liu, *J. Am. Chem. Soc.* **2016**, *138*, 8588–8594; b) X. Qi, X. Liu, L.-B. Qu, Q. Liu, Y. Lan, *J. Catal.* **2018**, *362*, 25–34.

[51] V. G. Landge, J. Pitchaimani, S. P. Midya, M. Subaramanian, V. Madhu, E. Balaraman, *Cat. Sci. Technol.* **2018**, *8*, 428–433.

[52] Y.-P. Zhou, Z. Mo, M.-P. Luecke, M. Driess, *Chem. Eur. J.* **2018**, *24*, 4780–4784.

[53] A. Brzozowska, L. M. I. Azofra, V. Zubar, I. Atodiresei, L. Cavallo, M. Rueping, O. El-Sepelgy, *ACS Catal.* **2018**, *8*, 4103–4109.

[54] J. Sklyaruk, V. Zubar, J. C. Borghs, M. Rueping, *Org. Lett.* **2020**, *22*, 6067–6071.

[55] D. Srimani, Y. Diskin-Posner, Y. Ben-David, D. Milstein, *Angew. Chem.* **2013**, *125*, 14131–14134; *Angew. Chem., Int. Ed.* **2013**, *52*, 14381–14384.

[56] K. Tokmic and A. R. Fout, *J. Am. Chem. Soc.*, 2016, **138**, 13700–13705.

[57] S. R. Muhammad, J. W. Nugent, K. Tokmic, L. Zhu, J. Mahmoud, A. R. Fout, *Organometallics* **2019**, *38*, 3132–3138.

[58] N. Gorgas, J. Brünig, B. Stöger, S. Vanicek, M. Tilset, L. F. Veiros, K. Kirchner, *J. Am. Chem. Soc.* **2019**, *141*, 17452–14458.

[59] K. Murugesan, C. B. Bheeter, P. R. Linnebank, A. Spannenberg, J. N. H. Reek, R. V. Jagadeesh, M. Beller, *ChemSusChem* **2019**, *12*, 3363–3369.

[60] V. Zubar, J. Sklyaruk, A. Brzozowska, M. Rueping, *Org. Lett.* **2020**, *22*, 5423–5428.

[61] C. F. de Graauw, J. A. Peters, H. van Bekkum, J. Huskens, *Synthesis* **1994**, 1007–1017.

[62] a) C. A. Sandoval, T. Ohkuma, K. Muniz, R. Noyori, *J. Am. Chem. Soc.* **2003**, *125*, 13490–13503; b) R. Langer, M. A. Iron, L. Konstantinovski, Y. Diskin-Posner, G. Leitus, Y. Ben-David, D. Milstein, *Chem - Eur. J.* **2012**, *18*, 7196–7209.

[63] J. Brandenburg, H. Baltes, R. Dach (2007), Method for the Production of 1,3-Dioxolane-2-Ones and Carboxylic Acid Esters by Means of Transacylation in Basic Reaction Conditions, US20100305146A1.

[64] M. Perez, S. Elangovan, A. Spannenberg, K. Junge, M. Beller, *ChemSusChem* **2017**, *10*, 83–86.

[65] a) A. Friedrich, S. Schneider, *ChemCatChem* **2009**, *1*, 72–73; b) C. Gunanathan, D. Milstein, Science **2013**, *341*, 1229712.

[66] J. S. M. Samec, J.-E. Bäckvall, P. G. Andersson, P. Brandt, *Chem. Soc. Rev.* **2006**, *35*, 237–248.

[67] J.-H. Choi, N. E. Schloerer, J. Berger, M. H. G. Prechtl, *Dalton Trans.* **2014**, *43*, 290–299.

[68] S. Elangovan, C. Topf, S. Fischer, H. Jiao, A. Spannenberg, W. Baumann, R. Ludwig, K. Junge, M. Beller, *J. Am. Chem. Soc*. **2016**, *138*, 8809–8814.

[69] ICH (International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use) guideline, "ICH guideline Q3D on elemental impurities", can be found under: https://www.ema.europa.eu/en/documents/scientific-guideline/international-conference-harmonisation-technical-requirements-registration-pharmaceuticals-human-use_en-32.pdf, **2021**.

9 Selected Publications

The following chapter contains the original publications wherein the previously presented research was reported. My contribution to each chapter is outlined in the subchapters:

9.1 Iron–PNP-Pincer-Catalysed Transfer Dehydrogenation of Secondary Alcohols

S. Budweg, Z. Wei, H. Jiao, K. Junge and M. Beller

ChemSusChem **2019**, *12*, 2988–2993.

DOI: 10.1002/cssc.201900308

In this paper, I synthesised the investigated complex and optimised the reaction conditions for the dehydrogenation of secondary alcohols. Furthermore, I performed the substrate scope including the product isolation and the evaluation of the analytical data. I wrote the first draft of the manuscript, as well as the supporting information. Computations were done by Zhihong Wei and Haijun Jiao. My contribution amounts to 70%.

ChemPubSoc Europe

DOI: 10.1002/cssc.201900308

CHEMSUSCHEM Communications

Iron–PNP-Pincer-Catalyzed Transfer Dehydrogenation of Secondary Alcohols

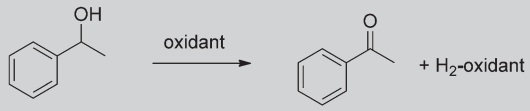
Svenja Budweg, Zhihong Wei, Haijun Jiao, Kathrin Junge, and Matthias Beller*[a]

The well-defined iron PNP pincer complex catalyst $[Fe(H)(BH_4)(CO)(HN\{CH_2CH_2P(iPr)_2\}_2]$ was used for the catalytic dehydrogenation of secondary alcohols to give the corresponding ketones. Using acetone as inexpensive hydrogen acceptor enables the oxidation with good to excellent yields. DFT computations indicate an outer-sphere mechanism and support the importance of an acceptor to achieve this transformation under milder conditions.

In the context of using renewable resources, oxidation of bio-based alcohols offers possibilities for a more sustainable synthesis of aldehydes and ketones.[1] In traditional oxidation methods, stoichiometric amounts of chromium- or manganese-based reactants have been used. These oxidants are hazardous and environmentally harmful and large quantities of noxious waste are produced.[2] Hence, in recent decades the use of transition metal complexes in the presence of more environmentally friendly oxidants such as molecular oxygen and hydrogen peroxide has become an important field in catalysis and green chemistry.[3] Clearly, these latter methodologies are advantageous in terms of eco-friendliness and atom economy.[4]

The theoretical atom efficiencies for several such oxidation methods are given in Table 1 for the typical model reaction of 1-phenylethanol to acetophenone comparing different oxidants. Thus, acceptorless alcohol dehydrogenations (ADH) attracted significant interest in recent years.[6] Advantageously, these reactions require no strong oxidant and hydrogen is produced as the only byproduct.[7] However, from a thermodynamic point of view, ADH is endothermic at ambient temperature and therefore high temperatures are necessary to shift the equilibrium towards the desired ketone.[8] Milder reaction conditions can be attained by the use of acceptors, which are able to take up the formed hydrogen and thus have a favorable effect on ketone formation.[9] In this respect, acetone is an inexpensive, readily available and nontoxic option, which can also be produced from renewables, namely lignocelluloses through ABE fermentation.[10] As early as 1937, the first reaction

Table 1. Theoretical atom efficiency of selected oxidation methods for conversion of 1-phenylethanol into acetophenone.[5]



Oxidation method	Atom efficiency [%]	Waste
Acceptorless dehydrogenation	98	H_2
Dehydrogenation with O_2	87	H_2O
Dehydrogenation with H_2O_2	77	H_2O
Transfer dehydrogenation with acetone as acceptor	67	isopropanol
Jones oxidation	42	H_2CrO_3, H_2O
Swern oxidation	28	$(CH_3)_2S$, CO_2, CO, Et_3NHCl

with acetone as the hydrogen acceptor was reported by Oppenauer, when he carried out the selective oxidation of steroids with an aluminum alkoxide catalyst.[11] Since then, numerous modifications of this so-called Oppenauer oxidation have been reported and applied to other catalytic systems.[12] The first attempt to dehydrogenate alcohols with noble metal complexes by means of this method was reported by Bäckvall and co-workers in 1996.[13] In their approach, two different ruthenium complexes (**1** and **2**, Figure 1) were employed, which were capable of dehydrogenating aromatic and aliphatic secondary alcohols in refluxing acetone.

In 2004, Severin and co-workers reported a heterobimetallic complex (**3**, Figure 1) for the dehydrogenation (DH) of primary and secondary alcohols at lower temperature and catalyst loading.[14] Notably in this work, also primary alcohols were oxidized to the corresponding aldehydes without the formation of by-products through aldol condensation. This transformation was also mediated by an iridium complex carrying an N-heterocyclic carbene ligand (**4**), which was developed by Yamaguchi and co-workers.[15] Recently, Binder, Ley, and co-workers reported a commercially available ruthenium complex (**5**) as an efficient DH catalyst in a continuous flow method.[16] In the same year, Hartwig and co-workers reported the selective oxidation of secondary alcohols with a ruthenium-based complex (**6**).[17] Despite the progress in this field, these catalytic systems all rely on precious metals. Since 2000, organometallic redox catalysis with pincer ligands has become a highly popular field of research.[18] In this regard, a variety of complexes based on non-noble metals have been applied in transfer hydrogenations, which can be regarded as the reverse reaction of acceptorless DH.[19] Indeed, several pincer catalysts based on manganese,[20] iron,[21] and cobalt[22] have been applied for this trans-

[a] S. Budweg, Z. Wei, Dr. H. Jiao, Dr. K. Junge, Prof. M. Beller
Leibniz-Institut für Katalyse e.V. an der Universität Rostock
Albert-Einstein Straße 29a, Rostock 18059 (Germany)
E-mail: matthias.beller@catalysis.de

Supporting Information and the ORCID identification number(s) for the author(s) of this article can be found under: https://doi.org/10.1002/cssc.201900308.

This publication is part of a Special Issue on "Sustainable Organic Synthesis". Please visit the issue at http://doi.org/10.1002/cssc.v12.13

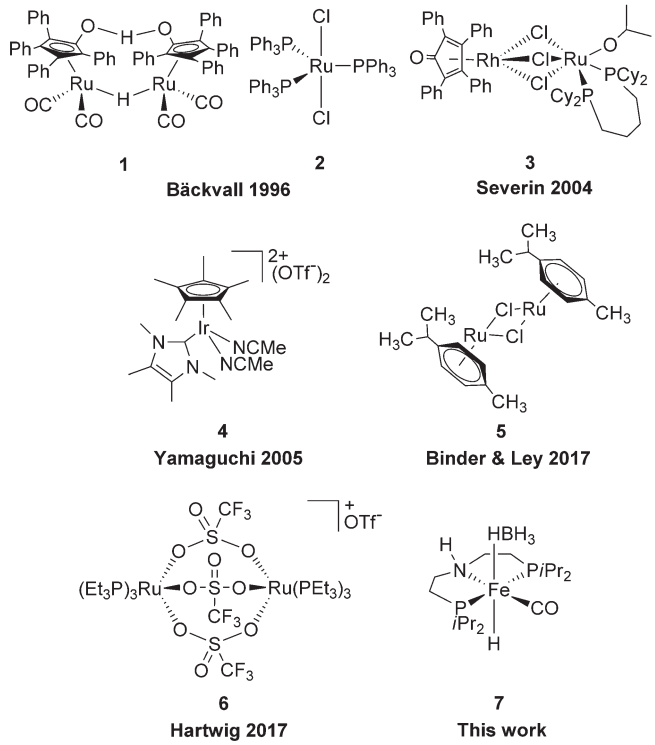
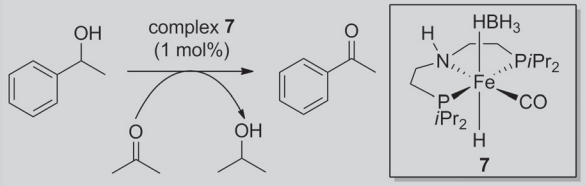


Figure 1. Complexes applied in transfer dehydrogenation of alcohols with acetone as hydrogen acceptor.

Table 2. Optimization of the reaction conditions with complex **7**.[a]



Entry	Base[b]	*t* [h]	*T* [°C]	Solvent[c]	Conv. [%]	Yield [%]
1	–	19	70	THF	14	12
2	NaO*t*Bu	19	70	THF	100	89
3[d]	NaO*t*Bu	19	70	THF	0	0
4	NaO*t*Bu	4	70	THF	100	91
5	NaO*t*Bu	4	50	THF	97	93
6	NaO*t*Bu	2	50	THF	57	53
7	NaO*t*Bu	2	50	heptane	84	73
8[e]	NaO*t*Bu	2	50	heptane	0	0
9[e,f]	NaO*t*Bu	2	50	heptane	17	13
10[f]	NaO*t*Bu	2	50	heptane	83	71
11	KO*t*Bu	2	50	heptane	94	84
12	KO*t*Bu	4	50	heptane	100	97

[a] Conversion and yield were determined by GC using hexadecane as an internal standard. [b] 5 mol% base loading. [c] 2.5 mL solvent, 2.5 mL acetone. [d] Reaction was carried out without **7**. [e] Reaction was carried out without acetone. [f] Reaction was carried out in an open system.

formation. In particular, iron can be readily used, owing to its low toxicity and high natural abundance, reflected also in the low cost of the metal.[3] Based on the previous work of our group on the DH of methanol using a defined iron pincer catalyst (**7**, Table 2), we became interested in the general performance of this catalyst for the dehydrogenation of alcohols with acetone as a hydrogen acceptor.[23]

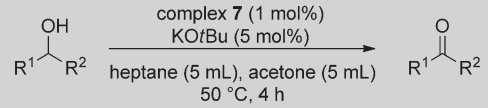
To find the optimal conditions for dehydrogenation catalysis, 1-phenylethanol was applied as benchmark substrate (Table 2). All initial tests were performed with 1 mol% of complex **7** while reaction temperatures, times, solvents, and bases were varied. Pincer complexes with a tetrahydridoborate ligand were used in various catalytic reactions even without added base, owing to the easy dissociation of BH_3 to form the active hydride complex.[24] However, in the case of dehydrogenation of methanol, the application of additional base had a favourable impact. Therefore, we utilized 5 mol% NaO*t*Bu as an additive.[22] Hereby an increase of the acetophenone yield from 12% to 89% was detected after 19 h reaction time at 70 °C (Table 2, entry 2).

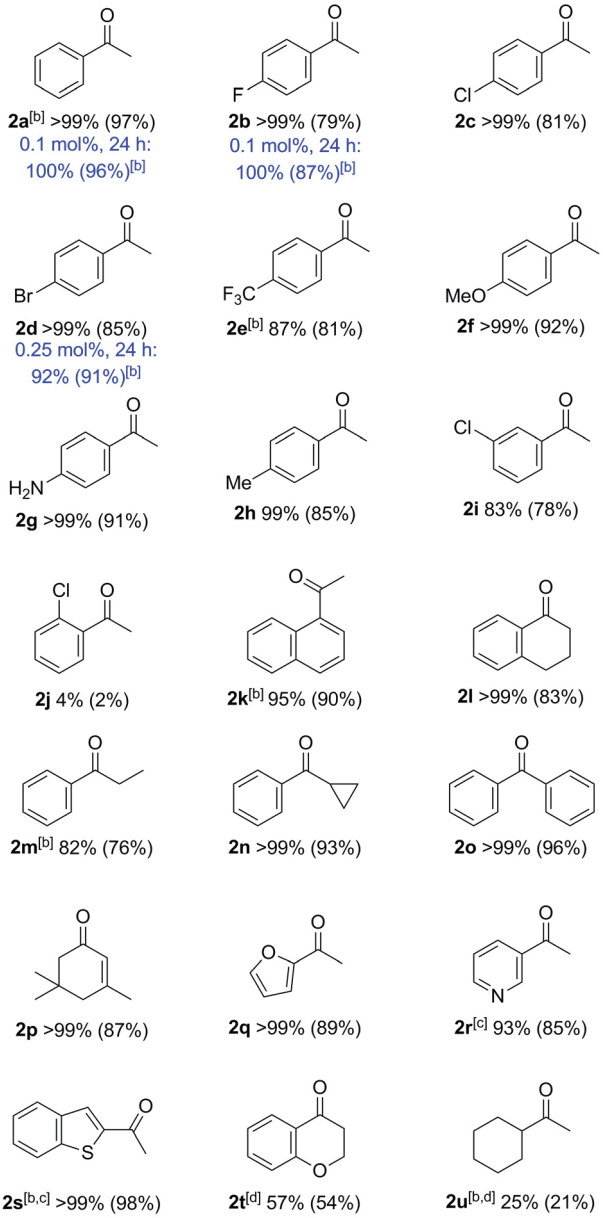
Hence, subsequent experiments were carried out by mixing 5 mol% of base alongside the catalyst in 2.5 mL tetrahydrofuran, followed by the addition to the substrate dissolved in acetone. To rule out simple base catalysis, the reaction was tested without complex **7** under similar conditions, which resulted in no dehydrogenation of the substrate at all (Table 2, entry 3). Full conversion was detected already after 4 h, furnishing acetophenone in 91% yield (Table 2, entry 4). Moreover, by reducing the temperature to 50 °C, a slightly higher yield of 93% and 97% conversion of the substrate into the corresponding ketone was obtained (Table 2, entry 5). To investigate the effect of solvent and base, we shortened the reaction time to 2 h to facilitate comparison of the obtained results. Changing the solvent for complex **7** from tetrahydrofuran to heptane resulted in an increase in yield from 53% to 73% (Table 2, entries 6 and 7).

The benefit of a hydrogen acceptor becomes clear when the reaction is performed without acetone, leading to no detectable dehydrogenation taking place (Table 2, entry 8). Conducting the experiment in an open system favors acceptorless DH through H_2 loss, but only 13% yield of acetophenone was detected (Table 2, entry 9). The use of acetone significantly enhanced the yield to 71%, similar to the reaction in a closed system (Table 2, entries 7 and 10). Moreover, we also tested the impact of different bases. 5 mol% of KO*t*Bu led to the best results, with yields of 84% after 2 h and 97% after 4 h (Table 2, entries 11 and 12).

After establishing optimal reaction parameters (1 mol% **7**, 5 mol% KO*t*Bu, 50 °C, 4 h, 5 mL heptane, 5 mL acetone), the general applicability of the iron catalyst was studied (Table 3). Overall, complex **7** was efficient for the oxidation of differently functionalized aromatic alcohols, as well as heterocyclic aromatic substrates. *Para*-substituted acetophenone derivatives carrying electron-donating or electron-withdrawing groups were isolated in good yields (Table 3, **2b**–**h**). Only the strong −I effect of the trifluoromethyl substituent causes a lower conversion, but the substrate was still dehydrogenated to the corresponding ketone with a yield of 81% (**2e**). Notably, the amino functionality was not oxidized during the catalytic reaction and the hydroxy group was therefore selectively dehydrogenated (**2g**). The presence of a chlorine atom in the *meta* po-

Table 3. Transfer dehydrogenation of (hetero)aromatic alcohols with complex **7**.[a]





[a] Reaction conditions (unless otherwise stated): substrate (1 mmol), complex **7** (0.01 mmol), KO*t*Bu (0.05 mmol), heptane (5 mL), acetone (5 mL), 50 °C, 4 h. Conversion was determined by GC using hexadecane as an internal standard. Values in parentheses refer to yields of isolated product. [b] GC yield. [c] Reaction conditions: substrate (1 mmol), complex **7** (0.02 mmol), KO*t*Bu (0.1 mmol), heptane (5 mL), acetone (5 mL), 50 °C, 24 h. [d] Reaction conditions: substrate (1 mmol), complex **7** (0.02 mmol), KO*t*Bu (0.1 mmol), heptane (5 mL), acetone (5 mL), 80 °C, 24 h.

sition led to slightly lower conversion, but nevertheless the ketone was isolated with 78% yield (**2i**). In the case of the *ortho*-substituted alcohol, the yield dropped significantly, which indicates that sterically demanding substrates are less active (**2j**). As an example of an annulated arene, 1-(naphthalen-1-yl)ethanol was oxidized with 95% conversion, leading to a high yield of 90% (**2k**).

Furthermore, α-tetralol was fully converted and isolated in 83% yield (Table 3, **2l**). When the steric demand was increased at the α-position to the carbonyl function, yields ranging from 76% to 96% were achieved (**2m**–**o**). Unfortunately, 2,2,2-trifluoro-1-phenylethanol, which is a more electron-poor substrate owing to the strong electron-withdrawing effect of the trifluoromethyl group, could not be transformed into the desired ketone. Next, we examined the oxidation of 3,5,5-trimethylcyclohex-2-en-1-ol and observed full conversion and 87% yield (**2p**). This finding indicates that allylic substrates can be easily dehydrogenated under these conditions. However, to suppress competing Michael additions, they have to be blocked at the β-position to the hydroxy group. Additionally, various heteroaromatic substrates were successfully dehydrogenated in yields up to 98% (**2q**–**t**). Finally, as part of the substrate screening, 1-cyclohexylethanol was tested as a standard substrate for aliphatic alcohols. In this case, a higher catalyst loading of 2 mol% **7** and 80 °C for 24 h was necessary to observe modest activity (**2u**).

From a sustainability point of view, it is important to reuse the excess solvent and oxidant. Hence, we carried out solvent recycling experiments using 1-(4-biphenylyl)-1-ethanol as substrate. Gratifyingly, the desired ketone was isolated in 87% yield by dehydrogenation in the recovered solvent (for details, see the Supporting Information).

Next, to elucidate the reaction mechanism and explore the experimental results, B3PW91 density functional theory computations were carried out for the benchmark reaction. According to previous experimental and theoretical studies using Fe–PNP pincer complexes for hydrogenation reactions,[25] as well as self-transfer hydrogenation and isomerization reaction,[26] we followed the reported computational procedure and the proposed outer-sphere mechanism for our computations (for details, see the Supporting Information). For the general aspect of the reaction mechanism, the reaction of the former benchmark substrate (**2a**) was used for our calculations. As indicated in the Supporting Information, the inclusion of dispersion and solvation effects did not reproduce the experimentally observed kinetic and thermodynamic results.

The first step in the mechanism is the dehydrogenation of 1-phenylethanol to acetophenone by the amido complex **1Fe**, which is converted into the amine complex **2Fe** (Figure 2) The second step is the hydrogenation of acetone to isopropanol by **2Fe**, which is converted back into **1Fe**. As a side reaction, and also without hydrogen acceptor, the amine complex **2Fe** can also lose H_2 to form the amido complex **1Fe**. In this case, only the dehydrogenation of 1-phenylethanol will take place. The release of traces of H_2 was confirmed by GC-MS (for details, see the Supporting Information).

When the release of H_2 was taken into account, the acceptorless dehydrogenation of 1-phenylethanol to acetophenone and H_2 is endergonic by 6.3 kJ mol^{-1}, whereas the transfer de-

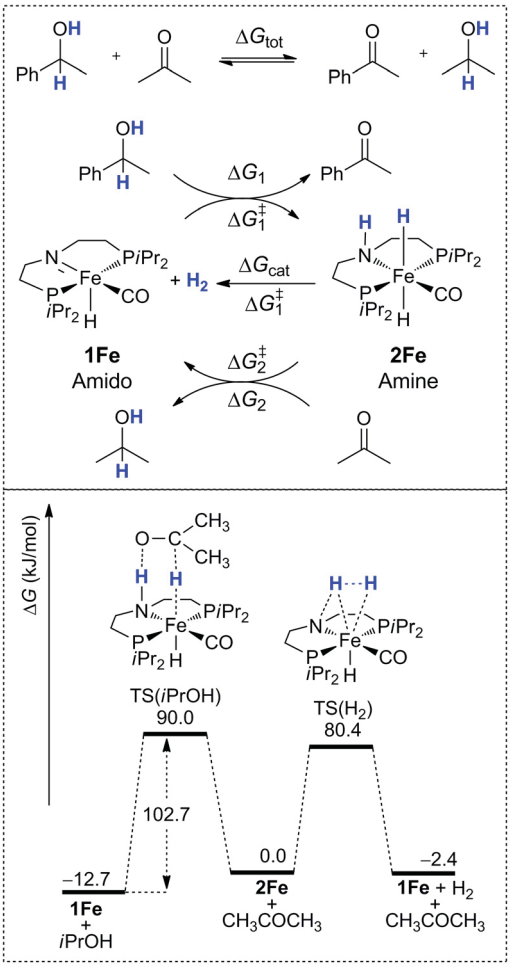


Figure 2. Proposed reaction sequences for the benchmark dehydrogenation as well as the reaction coordinates for the interconversion of catalysts [2Fe = 1Fe + H_2] and hydrogen acceptor [acetone + H_2 = isopropanol].

hydrogenation with acetone as acceptor is exergonic by 4.0 kJ mol^{-1}. This is favorable thermodynamically and explains the rather low yield for the reaction without acetone in comparison to the high yield with acetone in an open system (Table 2, entries 9 and 10). On the basis of the reaction free energy, the slightly endergonic acceptorless dehydrogenation of 1-phenylethanol needs high temperature to achieve reasonable yield, and the exergonic transfer dehydrogenation of 1-phenylethanol and acetone can be performed under milder conditions.

In a previous study,[26] it was found that exchange between the amine (**2Fe**) and amido (**1Fe**) complexes under H_2 release has a free energy barrier ($\Delta G_{cat}^{\ddagger}$) of 80.4 kJ mol^{-1} and is slightly exergonic (ΔG_{cat}) by 2.4 kJ mol^{-1}, indicating the reversibility and equilibrium under H_2 environment. These kinetic and thermodynamic parameters reveal these complexes to be effective catalysts for hydrogenation and dehydrogenation reactions. The barrier height is also a parameter for determining the catalyst stability under the reaction conditions.

Additionally, the dehydrogenation of 1-phenylethanol to acetophenone without hydrogen acceptor was computed at the same level of theory (B3PW91). As in case of the transition state of the interconversion between acetone and isopropanol, only one-step asynchronous authentic transition states for all hydrogenation reactions were located and identified. The dehydrogenation has a barrier of 100.8 kJ mol^{-1} and is endergonic (ΔG_1) by 8.7 kJ mol^{-1}. This underlines the experimental results in a closed system, since no detectable dehydrogenation took place in the absence of a hydrogen acceptor (Table 2, entry 8). In contrast, an open system enables acceptorless DH and release of H_2 but would require higher temperatures to accelerate the reaction (Table 2, entry 9). In contrast, when acetone is used as hydrogen acceptor, the hydrogenation of acetone to isopropanol has a barrier ($\Delta G_2^{\ddagger}$) of 90.0 kJ mol^{-1} and is exothermic (ΔG_2) by 12.7 kJ mol^{-1}. Moreover, the total transfer hydrogenation is exothermic (ΔG_{tot}) by 4.0 kJ mol^{-1}, indicating the well-balanced equilibrium under stoichiometric conditions. The computed equilibrium constant is 4.43, indicating that an excess of acetone is required to achieve a higher yield of acetophenone.

As a second example, the transfer dehydrogenation from allyl alcohol to ketone via the α,β-unsaturated carbonyl compound **2p** was computed (Figure 3). The allyl alcohol dehydro-

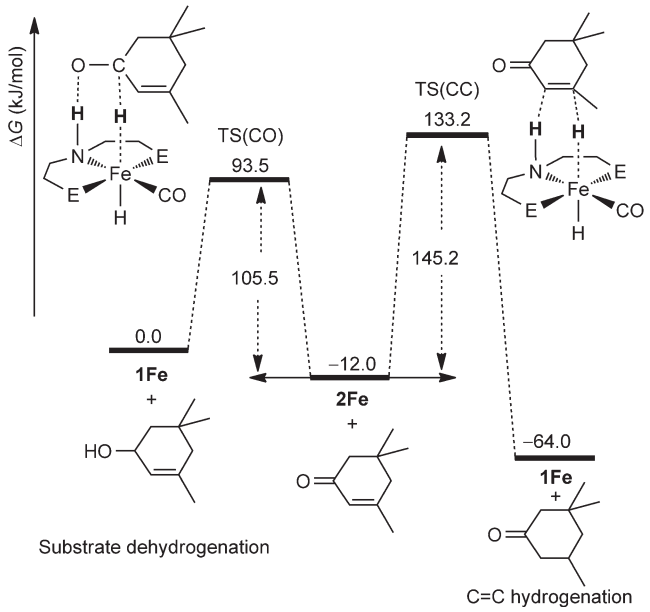


Figure 3. Energetics of the catalyzed dehydrogenation of allyl alcohol 2p and self-transfer isomerization.

genation has a barrier of 105.5 kJ mol^{-1}. This step is exergonic by 12 kJ mol^{-1} and thermodynamically favored; expecting complete conversion (>99%) and high yield (87% isolated). The C=C hydrogenation of 3,5,5-trimethylcyclohex-2-en-1-one has a barrier of 145.2 kJ mol^{-1} and is exergonic by 64 kJ mol^{-1}. Under the equilibrium conditions, the barrier to C=O hydrogenation is lower than that to C=C hydrogenation (105.5 vs. 145.2 kJ mol^{-1}) and, therefore, C=C hydrogenation is not competitive. Accordingly, only the first transfer hydrogenation step is possible and self-transfer hydrogenation is not favored kinetically, in agreement with the experiment. Apparently, the C=C

bond hydrogenation of the α,β-unsaturated ketone requires a much higher temperature.

In conclusion, we have presented herein a well-defined iron pincer complex $[Fe(H)(BH_4)(CO)(HN\{CH_2CH_2P(iPr)_2\}_2]$ for the catalytic dehydrogenation of secondary alcohols to give the corresponding ketones. This transformation proceeded under milder conditions than acceptorless dehydrogenations. However, it required the presence of acetone as an (inexpensive) hydrogen acceptor. DFT computations suggested an outer-sphere mechanism and supported the proposed beneficial effect of acetone, which shifts the endergonic acceptorless dehydrogenation to an exergonic transfer dehydrogenation process.

Experimental Section

General procedure for the catalytic transfer dehydrogenation

Under an argon atmosphere, a glass vial (4 mL) was charged with complex **7** (4 mg, 0.01 mmol, 1 mol%), KO*t*Bu (5.6 mg, 0.05 mmol, 5 mol%) and dry heptane (5 mL). The pink solution was stirred for 2 min at room temperature. A flame-dried Schlenk tube (25 mL) under an argon atmosphere served as reaction vessel and the alcohol (1 mmol) and dry acetone (5 mL) were added. The solution of catalyst and base was transferred via syringe into the Schlenk tube under thorough stirring. The vessel was then heated up and kept at 50 °C for 4 h in an alloy block. After the reaction time, the Schlenk tube was cooled to room temperature and an aliquot was taken for determination of conversion by GC analysis. Purification was accomplished by column chromatography and characterization by NMR spectroscopy and GC-MS.

Acknowledgements

This work was supported by the State of Mecklenburg-Western Pomerania and the BMBF. The analytic department of LIKAT is acknowledged for excellent analytical and technical support. Furthermore, we thank D. K. Leonard and J. Schneekönig for helpful comments.

Conflict of interest

The authors declare no conflict of interest.

Keywords: homogeneous catalysis · iron · oxidation · pincer ligands · transfer dehydrogenation

[1] I. W. C. E. Arends, R. A. Sheldon in *Modern Oxidation Methods, Vol. 2* (Ed.: J.-E. Bäckvall), Wiley-VCH, Weinheim, **2010**, pp. 147 – 180.
[2] G. Tojo, M. Fernández, *Oxidations of Alcohols to Aldehydes and Ketones*, Springer, Heidelberg, **2006**, pp. 1 – 148.
[3] a) M. G. Coleman, A. N. Brown, B. A. Bolton, H. Guan, *Adv. Synth. Catal.* **2010**, *352*, 967 – 970; b) M. N. Kopylovich, A. P. C. Ribeiro, E. C. B. A. Alegria, N. M. R. Martins, L. M. D. R. S. Martins, A. J. L. Pombeiro, *Adv. Organomet. Chem.* **2015**, *63*, 91 – 174; c) R. S. Drago, *Coord. Chem. Rev.* **1992**, *117*, 185 – 213; d) Z. Shi, C. Zhang, C. Tang, N. Jiao, *Chem. Soc. Rev.* **2012**, *41*, 3381 – 3430.
[4] a) Z. Wang, B. Pan, Q. Liu, E. Yue, G. A. Solan, Y. Ma, W.-H. Sun, *Catal. Sci. Technol.* **2017**, *7*, 1654 – 1661.
[5] a) B. M. Trost, *Science* **1991**, *254*, 1471 – 1477; b) F. Rajabi, A. Pineda, S. Naserian, A. M. Balu, R. Luque, A. A. Romero, *Green Chem.* **2013**, *15*, 1232 – 1237; c) T. Mallat, A. Baiker, *Chem. Rev.* **2004**, *104*, 3037 – 3058; d) K. Omura, D. Swern, *Tetrahedron Lett.* **1978**, *34*, 1651 – 1660.
[6] a) A. Mukherjee, D. Milstein, *ACS Catal.* **2018**, *8*, 11435 – 11469; b) W. Baratta, G. Bossi, E. Putignano, P. Rigo, *Chem. Eur. J.* **2011**, *17*, 3474 – 3481; c) S. Musa, I. Shaposhnikov, S. Cohen, D. Gelman, *Angew. Chem.* **2011**, *123*, 3595 – 3599; d) J. Zhang, E. Balaraman, G. Leitus, D. Milstein, *Organometallics* **2011**, *30*, 5716 – 5724; e) K.-N. T. Tseng, J. W. Kampf, N. K. Szymczak, *Organometallics* **2013**, *32*, 2046 – 2049; f) G. Zhang, K. V. Vasudevan, B. L. Scott, S. K. Hanson, *J. Am. Chem. Soc.* **2013**, *135*, 8668 – 8681; g) C. Gunanathan, D. Milstein, *Science* **2013**, *341*, 1229712; h) R. G. Alabau, M. A. Esteruelas, A. Martínez, M. Oliván, E. Oñate, *Organometallics* **2018**, *37*, 2732 – 2740.
[7] R. H. Crabtree, *Chem. Rev.* **2017**, *117*, 9228 – 9246.
[8] S. Chakraborty, P. O. Lagaditis, M. Förster, E. A. Bielinski, N. Hazari, M. C. Holthausen, W. D. Jones, S. Schneider, *ACS Catal.* **2014**, *4*, 3994 – 4003.
[9] C. F. de Graauw, J. A. Peters, H. van Bekkum, J. Huskens, *Synthesis* **1994**, 1007 – 1017.
[10] H. H. Khoo, W. L. Ee, V. Isoni, *Green Chem.* **2016**, *18*, 1912 – 1922.
[11] R. V. Oppenauer, *Recl. Trav. Chim. Pays-Bas* **1937**, *56*, 137 – 144.
[12] a) J. L. Namy, J. Souppe, J. Collin, H. B. Kagan, *Am. J. Org. Chem.* **1984**, *49*, 2045 – 2049; b) Y. Ishii, T. Nakano, A. Inada, Y. Kishigami, K. Sakurai, M. Ogawa, *Am. J. Org. Chem.* **1986**, *51*, 240 – 242; c) K.-J. Haack, S. Hashiguchi, A. Fujii, T. Ikariya, R. Noyori, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 285 – 288; *Angew. Chem.* **1997**, *109*, 297 – 300; d) G.-Z. Wang, J.-E. Bäckvall, *J. Chem. Soc. Chem. Commun.* **1992**, 337 – 339; e) Y. Nishibayashi, A. Yamachi, G. Onodera, S. Uemura, *J. Org. Chem.* **2003**, *68*, 5875 – 5880.
[13] M. L. S. Almeida, M. Beller, G.-Z. Wang, J.-E. Bäckvall, *Chem. Eur. J.* **1996**, *2*, 1533 – 1536.
[14] S. Gauthier, R. Scopelliti, K. Severin, *Organometallics* **2004**, *23*, 3769 – 3771.
[15] F. Hanasaka, K. Fujita, R. Yamaguchi, *Organometallics* **2005**, *24*, 3422 – 3433.
[16] R. Labes, C. Battilocchio, C. Mateos, G. R. Cumming, O. de Frutos, J. A. Rincón, K. Binder, S. V. Ley, *Org. Process Res. Dev.* **2017**, *21*, 1419 – 1422.
[17] C. K. Hill, J. F. Hartwig, *Nat. Chem.* **2017**, *9*, 1213 – 1221.
[18] Selected reviews from 2015 on: a) H. Valdés, M. A. García-Eleno, D. Canseco-Gonzalez, D. Morales-Morales, *ChemCatChem* **2018**, *10*, 3136 – 3172; b) S. Werkmeister, J. Neumann, K. Junge, M. Beller, *Chem. Eur. J.* **2015**, *21*, 12226 – 12250; c) T. Zell, D. Milstein, *Acc. Chem. Res.* **2015**, *48*, 1979 – 1994; d) S. Chakraborty, P. Bhattacharya, H. Dai, H. Guan, *Acc. Chem. Res.* **2015**, *48*, 1995 – 2003; e) S. Murugesan, K. Kirchner, *Dalton Trans.* **2016**, *45*, 416 – 419; f) E. Balaraman, A. Nandakumar, G. Jaiswal, M. K. Sahoo, *Catal. Sci. Technol.* **2017**, *7*, 3177 – 3195.
[19] a) D. Wang, D. Astruc, *Chem. Rev.* **2015**, *115*, 6621 – 6686; b) G. A. Filonenko, R. van Putten, E. J. M. Hensen, E. A. Pidko, *Chem. Soc. Rev.* **2018**, *47*, 1459 – 1483; c) K. Junge, V. Papa, M. Beller, *Chem. Eur. J.* **2019**, *25*, 122 – 143; d) L. Alig, M. Fritz, S. Schneider, *Chem. Rev.* **2019**, *119*, 2681 – 2751.
[20] a) M. Perez, S. Elangovan, A. Spannenberg, K. Junge, M. Beller, *ChemSusChem* **2017**, *10*, 83 – 86; b) M. Garbe, K. Junge, M. Beller, *Eur. J. Org. Chem.* **2017**, 4344 – 4362.
[21] a) K. Junge, K. Schröder, M. Beller, *Chem. Commun.* **2011**, *47*, 4849 – 4859; b) R. H. Morris, *Acc. Chem. Res.* **2015**, *48*, 1494 – 1502.
[22] a) G. Zhang, S. K. Hanson, *Chem. Commun.* **2013**, *49*, 10151 – 10153; b) Z. Shao, S. Fu, M. Wei, S. Zhou, Q. Liu, *Angew. Chem. Int. Ed.* **2016**, *55*, 14653 – 14657; *Angew. Chem.* **2016**, *128*, 14873 – 14877.
[23] E. Alberico, P. Sponholz, C. Cordes, M. Nielsen, H.-J. Drexler, W. Baumann, H. Junge, M. Beller, *Angew. Chem. Int. Ed.* **2013**, *52*, 14162 – 14166; *Angew. Chem.* **2013**, *125*, 14412 – 14416.
[24] a) C. A. Sandoval, T. Ohkuma, K. Muniz, R. Noyori, *J. Am. Chem. Soc.* **2003**, *125*, 13490 – 13503; b) R. Langer, M. A. Iron, L. Konstantinovski, Y. Diskin-Posner, G. Leitus, Y. Ben-David, D. Milstein, *Chem. Eur. J.* **2012**, *18*, 7196 – 7209.
[25] a) S. Werkmeister, H. Junge, B. Wendt, E. A. Alberico, H. Jiao, W. Baumann, K. Junge, F. Gallou, M. Beller, *Angew. Chem. Int. Ed.* **2014**, *53*,

8722 – 8726; *Angew. Chem.* **2014**, *126*, 8867 – 8871; b) C. Bornschein, S. Werkmeister, B. Wendt, H. Jiao, E. A. Alberico, W. Baumann, H. Junge, K. Junge, M. Beller, *Nat. Commun.* **2014**, *5*, 4111; c) H. Jiao, K. Junge, E. A. Alberico, M. Beller, *J. Comput. Chem.* **2016**, *37*, 168 – 176; d) S. Elangovan, B. Wendt, C. Topf, S. Bachmann, M. Scalone, A. Spannenberg, H. Jiao, W. Baumann, K. Junge, M. Beller, *Adv. Synth. Catal.* **2016**, *358*, 820 – 825; e) S. Lange, S. Elangovan, C. Cordes, A. Spannenberg, H. Jiao, H. Junge, S. Bachmann, M. Scalone, C. Topf, K. Junge, M. Beller, *Catal. Sci. Technol.* **2016**, *6*, 4768 – 4772; f) Z. Wei, H. Jiao in *Advances in Inorganic Chemistry, Vol. 73: Computational Chemistry* (Eds.: R. van Eldik, R. Puchta), Academic Press, Cambridge, MA, **2019**, pp. 323 – 384.

[26] T. Xia, Z. Wei, B. Spiegelberg, H. Jiao, S. Hinze, J. G. de Vries, *Chem. Eur. J.* **2018**, *24*, 4043 – 4049.

Manuscript received: January 31, 2019
Revised manuscript received: March 26, 2019
Accepted manuscript online: March 28, 2019
Version of record online: April 26, 2019

9.2 Transfer-dehydrogenation of secondary alcohols catalysed by manganese NNN-pincer complexes

S. Budweg, K. Junge and Matthias Beller

Chem. Commun. **2019**, *55*, 14143–14146.

DOI: 10.1039/C9CC07337J

In this paper, I synthesised the ligands and performed all experiments regarding the optimisation, substrate scope, and IR measurements. In addition, I evaluated the analytical data and wrote the first draft of the manuscript, as well as the supporting information. My contribution amounts to 80%.

ChemComm

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: *Chem. Commun.*, 2019, **55**, 14143

Received 18th September 2019,
Accepted 29th October 2019

DOI: 10.1039/c9cc07337j

rsc.li/chemcomm

Transfer-dehydrogenation of secondary alcohols catalyzed by manganese NNN-pincer complexes†

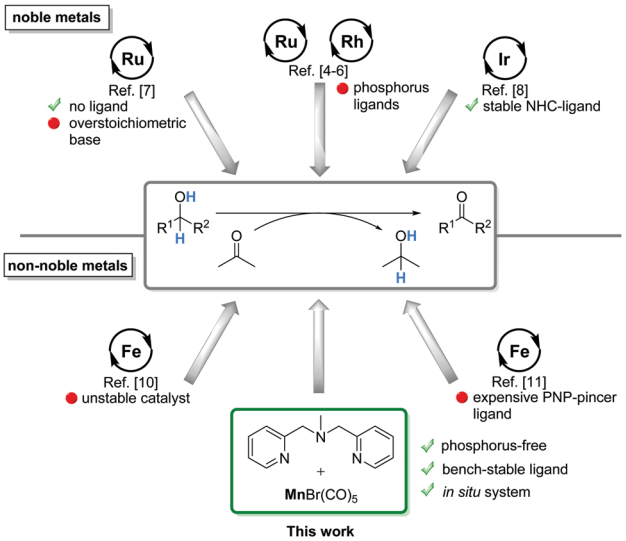
Svenja Budweg, Kathrin Junge and Matthias Beller *

Novel catalytic systems based on pentacarbonylmanganese bromide and stable NNN-pincer ligands are presented for the transfer-dehydrogenation of secondary alcohols to give the corresponding ketones in good to excellent isolated yields. Best results are obtained using di-picolylamine derivatives as ligands and acetone as an inexpensive hydrogen acceptor. Besides high activity for benzylic substrates, aliphatic alcohols, as well as steroid derivatives, are readily oxidized in the presence of the optimal phosphorus-free catalyst.

Transition-metal catalyzed transfer-dehydrogenation of alcohols constitutes an attractive method for selective alcohol oxidation.[1] Applying a suitable hydrogen acceptor, such as alkenes or carbonyl compounds, enables oxidations to occur under mild conditions.[2] In this respect, acetone is ideal as an inexpensive and non-toxic acceptor, which is typically used within the stoichiometric Oppenauer oxidation to synthesize ketones in the presence of aluminum alkoxides.[3] Following this approach, numerous catalytic systems have been reported for alcohol transfer-dehydrogenation, predominantly based on noble metals, specifically ruthenium. As an example, the Bäckvall group compared the reactivity of a ruthenium triphenylphosphine complex and the bimetallic Shvo's complex, which is well known for hydrogen transfer reactions.[4] In addition, a hetero bimetallic complex based on ruthenium and rhodium with sterically demanding phosphine ligands was later disclosed by Severin and co-workers.[5] More recently, the group of Hartwig developed a highly selective oxidation of secondary alcohols using a specific ruthenium complex with PEt_3 ligands.[6] Moreover, Binder and Ley implemented this technology in continuous flow systems using $[Ru(p\text{-cymene})\text{-}Cl_2]_2$ without additional ligands; however, overstoichiometric amounts of base were necessary for transfer-dehydrogenation in this case.[7] Apart from ruthenium, another approach made use of an iridium complex carrying a stable N-heterocyclic carbene ligand, which was published by the group of Yamaguchi in 2005.[8] Here, the low catalyst loading and the mild conditions are noteworthy.

In contrast, to the related transfer hydrogenation of ketones,[9] only two attempts have been reported so far to apply non-noble metal complexes for the transfer-dehydrogenation of alcohols in the presence of acetone. Originally, Guan and co-workers investigated Knölker's complex and related iron hydride catalysts for this transformation.[10] Lately, our group disclosed an iron PNP-pincer complex for such transformations (Scheme 1).[11]

Even though these oxidations proceed under comparable mild conditions, unfortunately the ligand is air-sensitive and not commercially available. Obviously, the ecologic and economic impact of any catalyst is not only determined by the choice of the metal. In fact, the required ligand can be many times more expensive due to challenging synthesis and difficulties in handling. For a long time (and still today), in homogeneous



Scheme 1 Transfer-dehydrogenation of alcohols using acetone as hydrogen acceptor.

Leibniz-Institut für Katalyse e.V. an der Universität Rostock, Albert-Einstein Straße 29a, Rostock 18059, Germany. E-mail: matthias.beller@catalysis.de

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c9cc07337j

catalysis the use of sensitive phosphine complexes is dominating. Not surprisingly, the vast majority of organometallic catalysts based on earth-abundant metals make use of highly sophisticated multidentate P-ligands. Hence, we started a program to develop more easily-accessible and phosphorus-free ligands, which are capable of forming active catalysts with non-noble metal precursors.

Manganese is among the most abundant metals in the earth's crust. Due to the broad range of oxidation states of manganese complexes/salts, it offers interesting possibilities for redox catalysis.[12] Hence, it is a promising candidate for the design of new (de)hydrogenation catalysts.[13] Indeed, in the last two years, manganese(I) pincer complexes have been shown to exhibit catalytic activity for several redox transformations and this field became a hot topic in homogenous catalysis.[14]

In search for a practical catalytic system for the model transfer-dehydrogenation of 1-phenylethanol, our work focused on *in situ* generated pre-catalysts based on $MnBr(CO)_5$ and chelating nitrogen ligands (Fig. 1). The initial screening was carried out using 0.5 mol% metal precursor and several different tridentate ligands (M : N = 1 : 3). After stirring the reaction mixture for 30 min at 90 °C a color change was observed and 0.5 mol% NaO*t*Bu, 1-phenylethanol and acetone were added consecutively. As shown in Fig. 1, diethylentriamine (**L1**) used as a ligand resulted in 71% yield of acetophenone. Interestingly, the introduction of a methyl group at the nitrogen atom of the secondary amine moiety (**L2**) led to complete inactivity.

A similar observation was made when the iPr-PyBOX ligand (**L3**) was used. Based on our group's previous success using a manganese catalyst with a di-picolylamine ligand **L4** for transfer hydrogenation,[15] we next tested this and related ligands **L5–L7**. Indeed, utilizing **L4** gave 65% conversion and 61% yield of acetophenone. To our surprise, both in the presence of the *N*-methylated di-picolylamine (**L5**, Me-dpa) as well as tris-(2-picolyl)amine (**L6**) full conversion and yields up to 98% were obtained. In order to allow for a more precise comparison, we recorded a concentration-time graph applying both ligands. As can be seen in Fig. 2, the catalytic system generated with **L5** provided excellent activity giving >80% conversion within the first ten minutes (97% after 30 min), whereas in the presence of **L6** 65% and 78% conversion were achieved after 10 and 30 minutes, respectively.

On the other hand, the application of terpyridine (**L7**) gave no conversion at all, implying that the methylene linkers of **L4–L6** play a crucial role for the catalytic activity in the TDH. For comparison, also pyridine-based phosphorus containing ligands (**L8**, **L9**) were tested under similar conditions, leading to no detectable product in case of **L8** and a reduced yield of 33% employing **L9**. As expected without any ligand present no conversion was observed, irrespective of whether or not base was deployed (Table 1, entries 1 and 2). Additionally, we examined further metal precursors for the reaction with ligand **L5**, but the system based on $MnBr(CO)_5$ remained best (for details see ESI,† Table S1).

Next, with the most active ligand **L5** in hand, we examined the influence of some critical reaction parameters. The reaction without base led to no conversion (Table 1, entry 3). A shorter preformation time of 15 min, furnished a slightly lower yield of product compared to 30 min and beyond (Table 1, entry 4). The ratio between precursor, ligand and base loading was maintained 1 : 1 : 1, in order to avoid aldol condensation of acetone by an excess of base, which leads to catalyst deactivation.

Lowering the catalyst and base loading to 0.1 mol% resulted in a decreased yield of 22% (Table 1, entry 5). Therefore, we decided to utilize 0.5 mol% loading of precursor, ligand and base. When applying a reaction temperature below 90 °C for the preformation and/or the reaction, inconsistent results were observed. Hence, we performed both the formation of the catalyst and the reaction at this temperature. Thus, only solvents with boiling

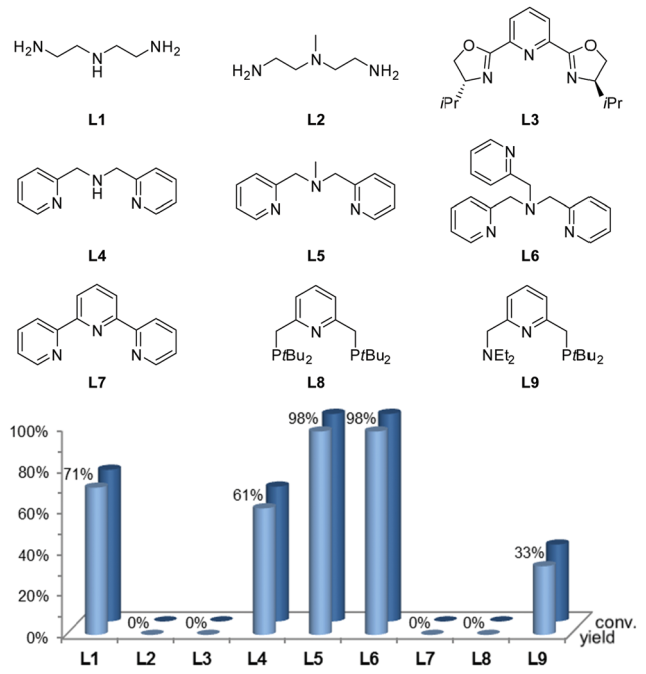


Fig. 1 Screening of ligands applied to the transfer-dehydrogenation of 1-phenylethanol. Reaction conditions: 1-phenylethanol (2 mmol), $MnBr(CO)_5$ (0.5 mol%), ligand (0.5 mol%), NaO*t*Bu (0.5 mol%), toluene (3 mL), acetone (1 mL), 90 °C, 2 h. Conversion and yield were determined by GC using hexadecane as internal standard.

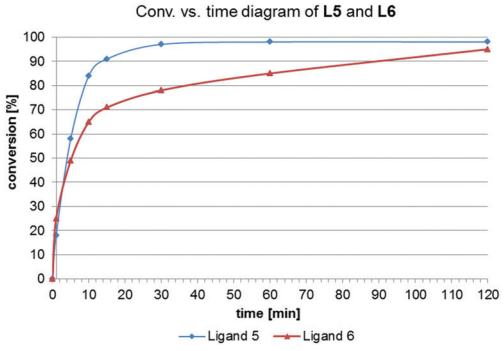
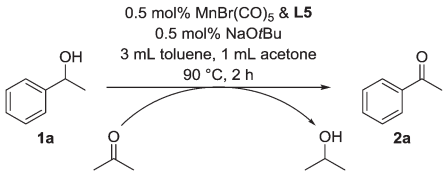


Fig. 2 Conversion *vs.* time diagram for the comparison of **L5** and **L6**. Reaction conditions: 1-phenylethanol (2 mmol), $MnBr(CO)_5$ (0.5 mol%), ligand (0.5 mol%), NaO*t*Bu (0.5 mol%), toluene (3 mL), acetone (1 mL), 90 °C. Conversion was determined by GC.

Table 1 Mn-Catalyzed transfer-dehydrogenation of 1-phenylethanol with $MnBr(CO)_5$ and ligand **L5**[a]



Entry	$MnBr(CO)_5$ [mol%]	Ligand [mol%]	Base [mol%]	Conv. [%]	Yield [%]
1	[0.5]	—	—	0	0
2	[0.5]	—	NaO*t*Bu [0.5]	0	0
3	[0.5]	**L5** [0.5]	—	0	0
4[b]	[0.5]	**L5** [0.5]	NaO*t*Bu [0.5]	94	93
5[c]	[0.1]	**L5** [0.1]	NaO*t*Bu [0.1]	24	22
6[d]	[0.5]	**L5** [0.5]	NaO*t*Bu [0.5]	92	90
7[e]	[0.5]	**L5** [0.5]	NaO*t*Bu [0.5]	98	96
8	[0.5]	**L5** [0.5]	NaO*t*Bu [0.5]	>99	98

[a] 1-Phenylethanol (2 mmol). Conversion and yield were determined by GC using hexadecane as an internal standard. [b] 15 min formation time. [c] 1-Phenylethanol (4 mmol), $MnBr(CO)_5$ (0.1 mol%), **L5** (0.1 mol%), NaO*t*Bu (0.1 mol%). [d] 1 h reaction time, heptane (3 mL), acetone (1 mL). [e] 1 h reaction time.

points higher than 90 °C (*e.g.*, heptane and toluene) were suitable for the reaction setup (Table 1, entries 6 and 7). In all experiments, acetone was therefore added shortly before closing the reaction vessel. Noticeably, in the absence of acetone no detectable dehydrogenation was observed, clearly showing the benefit of using an acceptor, while acceptorless dehydrogenation doesn't take place under given conditions.[16]

In summary, the reaction conditions chosen in the preliminary studies remained best and a reaction time of 2 h was selected for further studies.

To demonstrate the general applicability of the catalytic system, the transfer-dehydrogenation of 15 different benzylic alcohols was studied (Fig. 3). Noticeably, most of these substrates were effectively transformed to the corresponding ketones with low catalyst loading after a short reaction time (0.5 mol% $MnBr(CO)_5$, 0.5 mol% **L5**, 0.5 mol% NaO*t*Bu, 90 °C, 2 h, 3 mL toluene, 1 mL acetone). For example, *para*-substituted acetophenone derivatives bearing electron-donating or electron-withdrawing groups were isolated in high yields ranging from 83% to 98%. By switching the base from NaO*t*Bu to NaOMe, transesterification was prevented and the ester-containing methyl 4-acetylbenzoate (**2f**) was isolated with a good yield of 69%. Notably, the ester group remained stable under the given conditions. Furthermore, we examined the dehydrogenation of 1-(4-aminophenyl)ethanol and observed a selective oxidation of the hydroxyl group, furnishing the corresponding ketone with 98% yield (**2g**). Next, the reactivity of several β-substituted derivatives was studied. With ethyl or cyclopropyl groups, yields decreased to 81% (**2i**) and 49% (**2j**), respectively. Further derivatives bearing bulkier moieties required increased catalyst loadings and longer reaction times, whereby 67% benzophenone (**2k**) and 88% cyclohexyl phenyl ketone (**2l**) were isolated.

Furthermore, the presence of methoxy- or phenoxy-substituents in the β-position to the alcohol group is tolerated (**2m–n**).

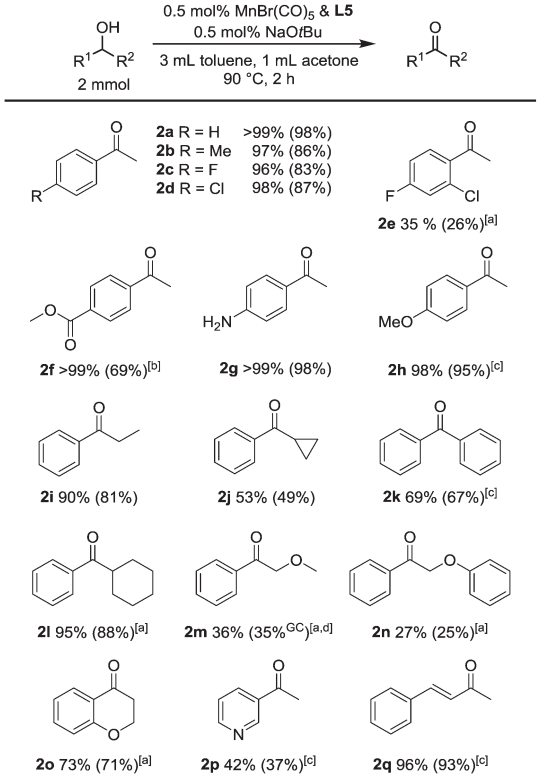


Fig. 3 Manganese-catalyzed dehydrogenation of benzylic alcohols. Conversion was determined by GC using hexadecane as an internal standard. Isolated yields are given in parentheses. [a] Substrate (1 mmol), $MnBr(CO)_5$ (5 mol%), **L5** (5 mol%), NaO*t*Bu (5 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. [b] Substrate (1 mmol), $MnBr(CO)_5$ (1 mol%), **L5** (1 mol%), NaOMe (1 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. [c] Substrate (1 mmol), $MnBr(CO)_5$ (1 mol%), **L5** (1 mol%), NaO*t*Bu (1 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. [d] GC yield.

Exemplary for hetero aromatic alcohols, chroman-4-ol (**1o**) and 3-(1-hydroxyethyl)pyridine (**1p**) were successfully dehydrogenated and isolated with 71% and 37% yield, respectively. Additionally, (*E*)-4-phenylbut-3-en-2-ol was oxidized to the corresponding α,β-unsaturated ketone (**2q**) in nearly quantitative yield without the detection of any side products.

To our delight, more demanding aliphatic alcohols were also dehydrogenated effectively (5 mol% $MnBr(CO)_5$, 5 mol% **L5**, 5 mol% NaO*t*Bu, 90 °C, 24 h, 6 mL toluene, 2 mL acetone). As shown in Fig. 4, the dehydrogenation of acyclic, as well as cyclic aliphatic substrates was examined and good to excellent yields were obtained. 3-Methyl-2-butanol and pinacolyl alcohol were effectively oxidized with 96% (**2r**) and 91% (**2s**) yield, respectively. Varying the ring size of the cyclic alcohols had only a minor influence on the catalyst activity and the corresponding ketones were obtained with excellent yields up to 96% (**2t–2v**).

Moreover, we studied the dehydrogenation of cyclohexanol and structurally related compounds and obtained the corresponding ketones with high yields of 78% to 92%. For trimethylcyclohex-2-en-1-ol (**1y**) full conversion to the corresponding ketone was detected. The oxidation of 2-cyclohexenol (**1x**) was achieved without any competing side reactions, despite the likelihood of it acting as an effective Michael acceptor due to the conjugated

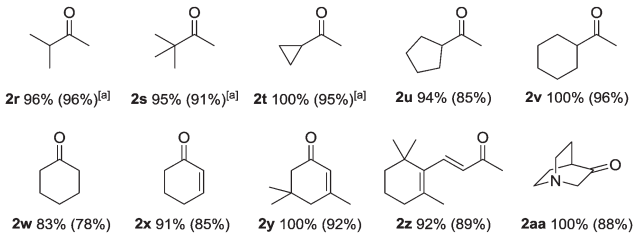


Fig. 4 Manganese-catalyzed dehydrogenation of aliphatic alcohols. General reaction conditions: substrate (1 mmol), $MnBr(CO)_5$ (5 mol%), **L5** (5 mol%), NaO*t*Bu (5 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. Conversion was determined by GC using hexadecane as an internal standard. Isolated yields are given in parentheses. [a] GC yield.

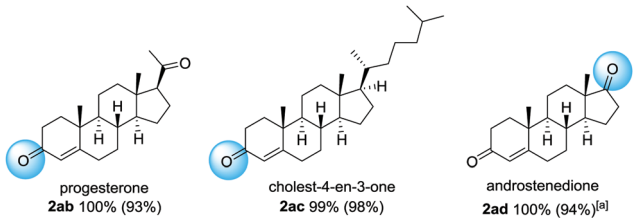


Fig. 5 Manganese-catalyzed dehydrogenation of aliphatic alcohols. General reaction conditions: substrate (1 mmol), $MnBr(CO)_5$ (5 mol%), **L5** (5 mol%), NaO*t*Bu (5 mol%), toluene (6 mL), acetone (2 mL), 90 °C, 24 h. Conversion was determined by GC using hexadecane as an internal standard. Isolated yields are given in parentheses. [a] 48 h reaction time.

double bond. Furthermore, the allylic substrate **1z**, which is frequently used in the fragrance industry, was effectively transformed to β-ionone (**2z**). Similarly, conversion of quinuclidine-3-ol was accomplished, yielding 88% of the corresponding ketone (**2aa**).

Finally, we tested the dehydrogenation of natural steroids bearing secondary alcohol moieties to showcase the utility of the catalytic system for modification of bio-active compounds (Fig. 5).

Thus, 3β-hydroxypregn-5-en-20-one and cholest-5-en-3β-ol were converted entirely to the corresponding ketones using 5 mol% $MnBr(CO)_5$, 5 mol% **L5** and 5 mol% NaO*t*Bu at 90 °C, furnishing progesterone (**2ab**) in 93% yield and cholest-4-en-3-one (**2ac**) in 98% yield after 24 h. Noticeably, a selective isomerization of the double bond occurred (>99%) to produce the more stable enone products. Moreover, testosterone was fully oxidized to androstenedione (**2ad**) and isolated in excellent yield of 94%.

Importantly, the use of the isolated complex [Mn(Me-dpa)-$(CO)_3$]Br in the dehydrogenation of 1-phenylethanol showed similar activity compared to the *in situ* formed catalyst.

Performing *in situ* IR spectroscopic investigations under catalytic conditions revealed characteristic CO bands at 2030, 1935 and 1920 cm^{-1} for the *in situ* generated species dissolved in heptane, as well as for the isolated complex (for details see ESI,† Fig. S1). The intensities of the carbonyl bands increased with higher temperature, due to better solubility. After activation by base (NaO*t*Bu), a slight decrease of the original CO bands is observed and a new band at 1808 cm^{-1} appeared indicating that in both cases the same catalytic active species is formed.

In conclusion, we present a convenient protocol for the transfer-dehydrogenation of secondary alcohols using acetone as inexpensive hydrogen acceptor. The conveniently *in situ* generated manganese catalyst is stabilized by a stable phosphorus-free NNN-pincer ligand allowing oxidation of aromatic and aliphatic alcohols.

Conflicts of interest

There are no conflicts to declare.

Notes and references

1 I. W. C. E. Arends and R. A. Sheldon, in *Modern Oxidation Methods*, ed. J.-E. Bäckvall, Wiley-VCH, Weinheim, 2010, vol. 2, pp. 147–180.
2 (*a*) J.-E. Bäckvall, R. L. Choudhury and U. Karlsson, *J. Chem. Soc., Chem. Commun.*, 1991, 473; (*b*) N. A. Owston, A. J. Parker and J. M. J. Williams, *Chem. Commun.*, 2008, 624; (*c*) A. V. Polukeev and O. F. Wendt, *Organometallics*, 2017, **36**, 639; (*d*) T. W. Funk, A. R. Mahoney, R. A. Sponenburg, K. P. Zimmerman, D. K. Kim and E. E. Harrison, *Organometallics*, 2018, **37**, 1133.
3 R. V. Oppenauer, *Recl. Trav. Chim. Pays-Bas*, 1937, **56**, 137.
4 (*a*) M. L. S. Almeida, M. Beller, G.-Z. Wang and J.-E. Bäckvall, *Chem. – Eur. J.*, 1996, **2**, 1533; (*b*) M. C. Warner, C. P. Casey and J.-E. Bäckvall, in *Bifunctional Molecular Catalysis*, ed. T. Ikariya and M. Shibasaki, Springer, Heidelberg, 2011, pp. 85–125.
5 S. Gauthier, R. Scopelliti and K. Severin, *Organometallics*, 2004, **23**, 3769.
6 J. F. Hartwig and C. K. Hill, *Nat. Chem.*, 2017, **9**, 1213.
7 R. Labes, C. Battilocchio, C. Mateos, G. R. Cumming, O. de Frutos, J. A. Rincón, K. Binder and S. V. Ley, *Org. Process Res. Dev.*, 2017, **21**, 1419.
8 K.-i. Fujita, F. Hanasaka and R. Yamaguchi, *Organometallics*, 2005, **24**, 3422.
9 (*a*) D. Wang and D. Astruc, *Chem. Rev.*, 2015, **115**, 6621; (*b*) S. Werkmeister, J. Neumann, K. Junge and M. Beller, *Chem. – Eur. J.*, 2015, **21**, 12226; (*c*) G. A. Filonenko, R. van Putten, E. J. M. Hensen and E. A. Pidko, *Chem. Soc. Rev.*, 2018, **47**, 1459; (*d*) N. Gorgas and K. Kirchner, *Acc. Chem. Res.*, 2018, **51**, 1558; (*e*) K. Junge, V. Papa and M. Beller, *Chem. – Eur. J.*, 2019, **25**, 122; (*f*) L. Alig, M. Fritz and S. Schneider, *Chem. Rev.*, 2019, **119**, 2681.
10 M. G. Coleman, A. N. Brown, B. A. Bolton and H. Guan, *Adv. Synth. Catal.*, 2010, **352**, 967.
11 S. Budweg, Z. Wei, H. Jiao, K. Junge and M. Beller, *ChemSusChem*, 2019, **12**, 2988.
12 (*a*) R. J. Trovitch, *Acc. Chem. Res.*, 2017, **50**, 2842; (*b*) M. Garbe, K. Junge and M. Beller, *Eur. J. Org. Chem.*, 2017, 4344; (*c*) F. Kallmeier and R. Kempe, *Angew. Chem., Int. Ed.*, 2018, **57**, 46; (*d*) T. Zell and R. Langer, *ChemCatChem*, 2018, **10**, 1930; (*e*) A. Mukherjee and D. Milstein, *ACS Catal.*, 2018, **8**, 11435.
13 (*a*) H. Valdés, M. A. García-Eleno, D. Canseco-Gonzalez and D. Morales-Morales, *ChemCatChem*, 2018, **10**, 3136; (*b*) D. Morales-Morales, *Pincer Compounds: Chemistry and Applications*, Elsevier, 2018.
14 Selected references: (*a*) F. Kallmeier, T. Irrgang, T. Dietel and R. Kempe, *Angew. Chem., Int. Ed.*, 2016, **55**, 11806; (*b*) N. Deibl and R. Kempe, *Angew. Chem., Int. Ed.*, 2017, **56**, 1663; (*c*) S. Fu, Z. Shao, Y. Wang and Q. Liu, *J. Am. Chem. Soc.*, 2017, **139**, 11941; (*d*) M. B. Widegren, G. J. Harkness, A. M. Z. Slawin, D. B. Cordes and M. L. Clarke, *Angew. Chem., Int. Ed.*, 2017, **56**, 5825; (*e*) A. Bruneau-Voisine, D. Wang, V. Dorcet, T. Roisnel, C. Darcel and J.-B. Sortais, *Org. Lett.*, 2017, **19**, 3656; (*f*) G. Zhang, T. Irrgang, T. Dietel, F. Kallmeier and R. Kempe, *Angew. Chem., Int. Ed.*, 2018, **57**, 9131; (*g*) Y. Wang, Z. Shao, K. Zhang and Q. Liu, *Angew. Chem., Int. Ed.*, 2018, **57**, 15143; (*h*) R. Fertig, T. Irrgang, F. Freitag, J. Zander and R. Kempe, *ACS Catal.*, 2018, **8**, 8525; (*i*) Z. Shao, Y. Wang, Y. Liu, Q. Wang, X. Fub and Q. Liu, *Org. Chem. Front.*, 2018, **5**, 1248; (*j*) H. Li, D. Wei, A. Bruneau-Voisine, M. Ducamp, M. Henrion, T. Roisnel, V. Dorcet, C. Darcel, J.-F. Carpentier, J.-F. Soule and J.-B. Sortais, *Organometallics*, 2018, **37**, 1271; (*k*) B. G. Reed-Berendt, K. Polidano and L. C. Morrill, *Org. Biomol. Chem.*, 2019, **17**, 1595; (*l*) O. El-Sepelgy, E. Matador, A. Brzozowska and M. Rueping, *ChemSusChem*, 2019, **12**, 3099.
15 M. Perez, S. Elangovan, A. Spannenberg, K. Junge and M. Beller, *ChemSusChem*, 2017, **10**, 83.
16 (*a*) A. Friedrich and S. Schneider, *ChemCatChem*, 2009, **1**, 72; (*b*) C. Gunanathan and D. Milstein, *Science*, 2013, **341**, 1229712; (*c*) R. H. Crabtree, *Chem. Rev.*, 2017, **117**, 9228.

9.3 Chemoselective semihydrogenation of alkynes catalysed by manganese(I)-PNP pincer complexes

M.Garbe, S. Budweg, V. Papa, Z. Wei, H. Hornke, S. Bachmann, M. Scalone, A. Spannenberg, H. Jiao, K. Junge and M. Beller

Catal. Sci. Technol. **2020**, *10*, 3994–4001.

DOI: 10.1039/D0CY00992J

This manuscript was prepared in cooperation with Dr. Marcel Garbe. I prepared the complex, participated during the testing of different catalysts, and helped optimising the reaction conditions. Moreover, I took part in the substrate scope and in the writing process of the manuscript. I mainly assessed the analytical data and wrote the supporting information. First and second author contributed equally to this publication and my work is about 40%.

Catalysis Science & Technology

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *Catal. Sci. Technol.*, 2020, **10**, 3994

Chemoselective semihydrogenation of alkynes catalyzed by manganese(I)-PNP pincer complexes†‡

Marcel Garbe,§[a] Svenja Budweg,§[a] Veronica Papa,[a] Zhihong Wei,[a] Helen Hornke,[a] Stephan Bachmann,[b] Michelangelo Scalone,[b] Anke Spannenberg,[a] Haijun Jiao,[a] Kathrin Junge *[a] and Matthias Beller *[a]

Received 14th May 2020,
Accepted 21st May 2020

DOI: 10.1039/d0cy00992j

rsc.li/catalysis

A general manganese catalyzed chemoselective semihydrogenation of alkynes to olefins in the presence of molecular hydrogen is described. The best results are obtained by applying the aliphatic Mn PNP pincer complex **Mn-3c** which allows the transformation of various substituted internal alkynes to the respective *Z*-olefins under mild conditions and in high yields. Mechanistic investigations based on experiments and computations indicate the formation of the *Z*-isomer *via* an outer-sphere mechanism.

Introduction

Olefins play an important role as synthetic building blocks for fine and bulk chemistry as well as in organic synthesis.[1] Additionally, alkenes and here especially the *Z*-isomers can be found as structural motifs in numerous biologically and pharmaceutically active compounds. Although various synthetic approaches for these compounds have been developed in the past, the selective reduction of C–C triple bonds to alkenes offers a convenient route.[2] In general, in this transformation the control of chemoselectivity (alkenes *vs.* alkanes) and the stereoselectivity (*E*- and/or *Z*-olefins) is important. A selective preparation of one single isomer strongly depends on the chosen reaction parameters as well as on the catalyst. Traditionally, the application of heterogeneous transition–metal catalysts such as the Lindlar catalyst[3a,b] (lead-poisoned Pd on $CaCO_3$) enables the selective semihydrogenation of alkynes to *Z*-olefins. Besides Pd,[3] other transition metals, such as Rh,[4] Ru,[5] Nb,[6] Cr,[7] and V,[8] have been reported for both heterogeneous and homogeneous catalysis.[9]

Based on the growing significance of sustainability and the shortage of resources, the development of cheap, more easily available, non-noble metal catalysts is of increasing importance. In this respect, catalytic systems derived from first row transition metals such as Ni,[10] Co,[11] Fe,[12] or Cu,[13] were studied for this reaction. Here, especially homogeneous pincer type catalysts have been applied for the (transfer) semihydrogenation of alkynes to alkenes.

The first example of a non-noble metal pincer based catalyst for the semihydrogenation of alkynes has been reported by Milstein and co-workers in 2013 (Fig. 1).[14a] More specifically, the acridine-based PNP iron complex **Fe-1** selectively reduced internal alkynes to the *E*-alkenes, while no additional base was required to obtain the desired products. Notably, the corresponding *E*-isomers were formed in high yields with *E*:*Z* ratios of up to 100:0 *via* rapid isomerisation of the originally formed *Z*-products. Very recently, the Kirchner group presented a cationic iron pincer complex **Fe-2** bearing an aminoborane ligand, which efficiently reduced internal alkynes under mild conditions to the respective *Z*-olefins.[14b]

Based on the pioneering work of Milstein, Co pincer ligated catalysts were published for the (transfer)

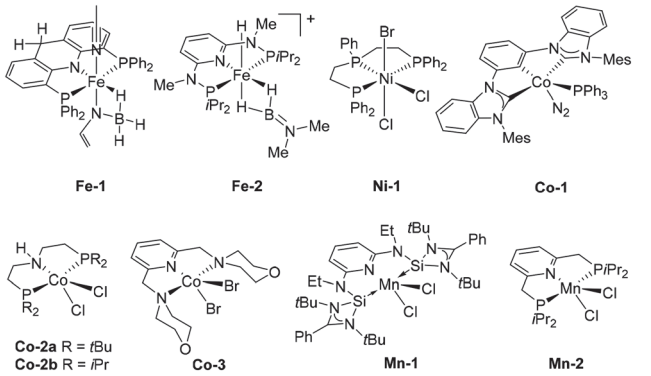


Fig. 1 Non-noble metal pincer-based catalysts for the (transfer) semihydrogenation of internal alkynes.

[a] *Leibniz-Institut für Katalyse e.V, Albert-Einstein-Straße 29a, Rostock, 18059, Germany. E-mail: Kathrin.Junge@catalysis.de, Matthias.Beller@catalysis.de*
[b] *F. Hoffmann-La Roche AG, Department of Process Chemistry & Catalysis, Basel, 4070, Switzerland*

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d0cy00992j

‡ Dedicated to Prof. Uwe Rosenthal on the occasion of his 70th birthday.

§ Both authors contributed equally to this publication.

semihydrogenation of alkynes to the *E*- or *Z*-isomers.[15] Thus, the Co CCC pincer complex **Co-1** is able to reduce alkynes with high selectivity to *trans*-alkenes.[15a] A broad range of substituted diphenylacetylenes was hydrogenated in high yields and *E*/*Z* ratios both with electron-donating and -withdrawing groups. Mechanistic studies showed that the corresponding *E*-alkenes are produced by initial *cis*-hydrogenation followed by *cis*/*trans*-isomerisation. Interestingly, Liu and co-workers developed a stereo-divergent Co-catalysed transfer hydrogenation of alkynes to *Z*- and/or *E*-alkenes.[15b,d] They observed that the stereocontrol for the semihydrogenation of alkynes strongly depends on the ligand type of the Co-pincer catalyst. Applying the Co PNP pincer complex **Co-2a** bearing bulky *t*-butyl substituents preferentially the *Z*-isomers are formed with ammonia borane as hydrogen source. The *E*-isomer is usually formed *via* isomerisation of the *Z*-alkene, which occurred on an open coordination site of the sterically less hindered metal centre of the catalyst. Notably, a slight change of the PNP-ligand structure from *t*-butyl (**Co-2a**) to i-propyl substituents (**Co-1b**) of the Co pincer complex resulted in a completely different stereoselectivity mainly yielding the *E*-alkenes. The phosphorous-free Co NNN pincer pre-catalyst **Co-3** also required ammonia borane for activation transforming internal alkynes to the *Z*-alkenes.[15c]

Furthermore, the Ni PPP pincer complex **Ni-1** was reported to convert 1,2-diphenylacetylene quantitatively to *E*-stilbene.[16]

Recently, also two manganese derived pincer type complexes were reported for the transfer semihydrogenation of internal alkynes.[17] Here, the N-heterocyclic silylene–manganese catalyst **Mn-1** produced the respective *E*-olefins, while with the manganese pre-catalyst [Mn(II)-PNP][Cl]$_2$ **Mn-2** the preferential formation of the *Z*-alkene was observed. Both catalytic systems worked at relatively low temperature for several substrates, but as a drawback equimolar amounts of borane adducts are required as hydrogen donor and for catalyst activation.

Although, a reasonable number of non-noble metal pincer-based catalyst was reported for the semihydrogenation of internal alkynes in the past years, examples of defined catalysts operating with molecular hydrogen are still limited. Herein, we present the development of the first manganese-based pincer catalyst which allows for the semihydrogenation of alkynes using inexpensive and atom-efficient H_2.

Results and discussion

Catalytic semihydrogenation of internal alkynes using manganese pincer complexes

At the start of our work, various manganese PNP,[18] NNP,[19] and NNN[20] pincer ligated complexes **Mn-3**–**Mn-7**, which were developed in our laboratory, were tested for hydrogenation of the model compound 1,2-diphenylethyne **1a** using 2 mol% catalyst and 5 mol% base loading at 30 bar H_2 and 50 °C (Fig. 2). Interestingly, the Mn complex **Mn-3a** with i-Pr$_2$P substituents in the PNP ligand backbone as well as the NNN

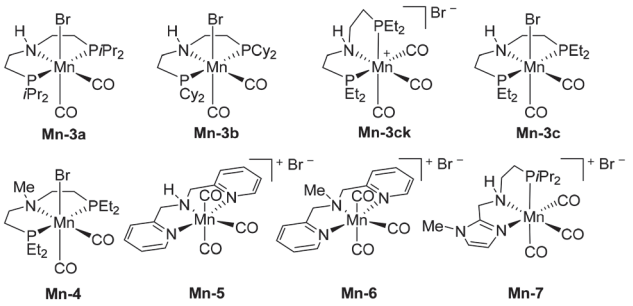


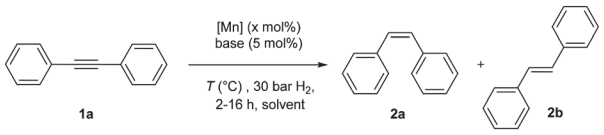
Fig. 2 Selection of manganese pincer based complexes tested in the semihydrogenation of 1,2-diphenylacetylene (**1a**).

Mn-5 and **Mn-6** and NNP ligated Mn species **Mn-7** provided only low or no reactivity (Table 1, entries 1, 5–7). In case of Mn pincer compounds **Mn-3b**, **Mn-3ck**, and **Mn-3c** complete conversion to the corresponding olefin **2a** was detected (entries 2–4), while exclusively the *Z*-isomer was formed. Notably, the neutral Mn pincer complex **Mn-3c** produced between 80–99% of the *Z*-stilbene in short reaction time (entries 8–12) and mild conditions (reaction temperature: 30 °C; entry 14). The excellent catalytic performance of this system is also demonstrated using only 0.5 mol% of pre-catalyst **Mn-3c** (entry 17). It is important to mention that in none of these reactions complete hydrogenation to the corresponding alkane was observed.

After the identification of the optimal Mn-pincer complex, the influence of different reaction parameters such as solvent and bases was further investigated (Table 2). In dichloromethane or various ethers only moderate yields of the *Z*-olefin were observed (entries 1–4), while the chemoselective formation of *cis*-stilbene **2a** stayed unaffected. Also, more polar alcoholic solvents completely failed to give the desired product (entries 5–6). In contrast, aprotic nonpolar solvents such as n-heptane and toluene proved to be suitable for this transformation producing the *cis*-alkene in yields above 90% (entries 7–10, 12). Notably, apart from KO*t*Bu, other bases such as NaO*t*Bu and KOH were tested using 1 mol% catalyst loading of **Mn-3c** (entries 8–10). Here, again complete conversion was obtained with KO*t*Bu, while NaO*t*Bu leads to slightly lower product yield. In case of KOH only poor reactivity was observed. A blank experiment using 5 mol% of KO*t*Bu without catalyst shows no conversion (entry 11).

The general applicability and the functional group tolerance of pre-catalyst **Mn-3c** were tested for diverse substrates (Scheme 1). Here, 20 different internal alkynes bearing (hetero)aromatic as well as alkyl moieties were efficiently reduced to the respective alkenes in good to high isolated yields with excellent *Z*-selectivities under comparably mild conditions (30 bar H_2, 30–60 °C). Alkynes with halide substituents such as fluorine (**1b**), chlorine (**2c**), bromine (**2d**–**e**) or the trifluoromethyl group (**2f**–**g**) are quantitatively transformed to the *cis*-olefins in 70–89% isolated yields. Additionally, ester (**1i**) and amine groups (**1o**, **1q**) on the alkynes were tolerated by the pincer complex **Mn-3c**

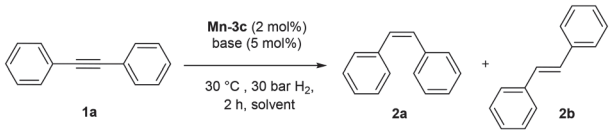
Table 1 Manganese-catalysed hydrogenation of 1,2-diphenylethyne **1a**: optimization of the reaction conditions[a]



Entry	Catalyst (mol%)	T (°C)	p (bar)	h	Conv. (%)	Yield **2a** (%)	Z/E
1	**Mn-3a** (2)	50	30	16	45	39	>99
2	**Mn-3b** (2)	50	30	16	97	93	>99
3	**Mn-3ck** (2)	50	30	16	>99	95	>99
4	**Mn-3c** (2)	50	30	16	>99	99	>99
5	**Mn-5** (2)	50	30	16	2	—	—
6[b]	**Mn-6** (2)	50	30	16	3	—	—
7[b]	**Mn-7** (2)	50	30	16	5.5	3	n.d.
8	**Mn-3b** (2)	50	30	5	61	59	97 : 3
9[b]	**Mn-3ck** (2)	50	30	5	60	56	97 : 3
10	**Mn-3c** (2)	50	30	5	>99	99	99 : 1
11	**Mn-3b** (2)	50	30	2	61	60	>99
12	**Mn-3c** (2)	50	30	2	>99	99	>99
13[c]	**Mn-4** (2)	50	30	2	2	—	—
14	**Mn-3c** (2)	30	30	2	73	67	>99
15	**Mn-3c** (1)	30	30	2	43	38	98 : 2
16[b]	**Mn-3c** (1)	30	30	4	>99	99	>99
17[b]	**Mn-3c** (0.5)	30	30	4	77	74	>99
18[b]	**Mn-3c** (1)	30	5	4	92	88	>99

[a] General conditions: 0.5 mmol substrate **1a**, 2 mol% catalyst **Mn-3**–**Mn-7**, 5 mol% NaO*t*Bu, 1 mL toluene. [b] 5 mol% KO*t*Bu; 1 mL heptane. [c] 2 mL heptane.

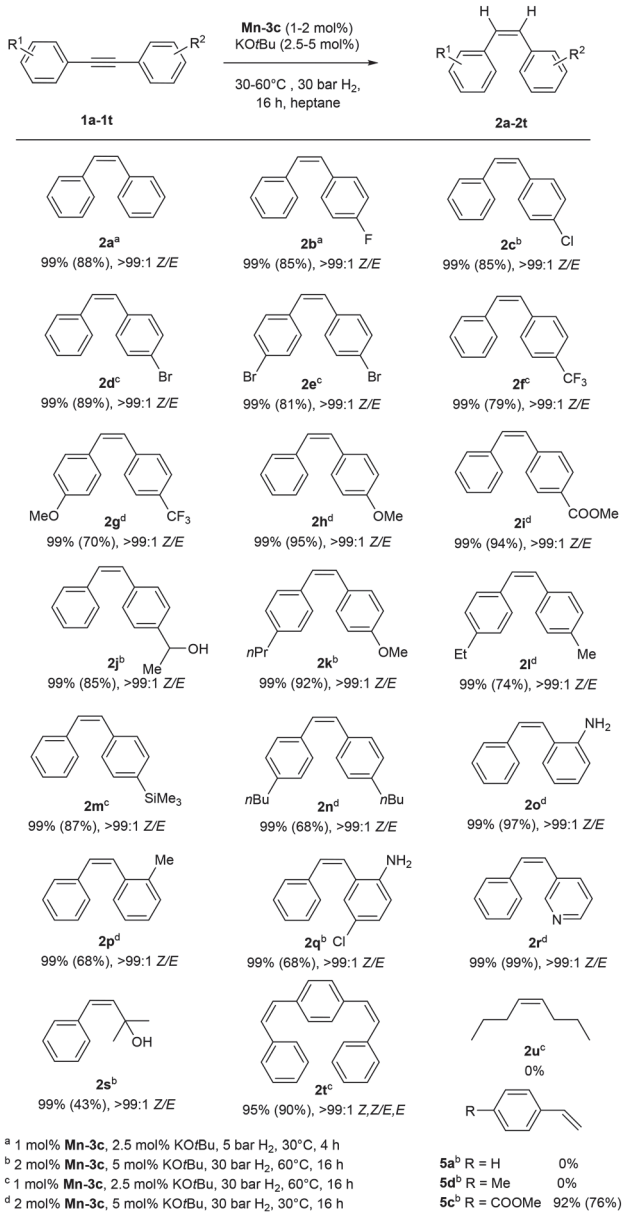
Table 2 Influence of solvents and bases for Mn-catalysed semihydrogenation of 1,2-diphenylethyne **1a**[a]



Entry	Solvent	Base	Conv. (%)	Yield **2a** (%)	Z/E
1	CH_2Cl_2	KO*t*Bu	25	21	97 : 3
2	Et_2O	KO*t*Bu	53	51	99 : 1
3	THF	KO*t*Bu	19	17	97 : 3
4	Dioxane	KO*t*Bu	26	23	97 : 3
5	*t*-AmylOH	KO*t*Bu	5	0	—
6	EtOH	KO*t*Bu	0	—	—
7	Heptane	KO*t*Bu	>99	>99	>99
8[b]	Heptane	KO*t*Bu	99	98	>99
9[b]	Heptane	NaO*t*Bu	88	86	>99
10[b]	Heptane	KOH	8	4	n.d.
11[c]	Heptane	KO*t*Bu	0	—	—
12	Toluene	KO*t*Bu	90	89	>99
13[d]	Toluene	KO*t*Bu	85	85	>99
14[d]	Toluene	—	3	2	n.d.

[a] General conditions: 0.5 mmol substrate, 2 mol% catalyst **Mn-3c**, 5 mol% KO*t*Bu, 1 mL solvent, 30 bar H_2, 30 °C, 2 h. [b] General conditions: 0.5 mmol substrate, 1 mol% **Mn-3c**, 5 mol% base, 1 mL heptane. [c] General conditions: 0.5 mmol substrate, 5 mol% KO*t*Bu, 1 mL solvent, 30 bar H_2, 30 °C, 2 h. [d] General conditions: 0.5 mmol substrate, 2 mol% catalyst **Mn-3ca**, 1 mL solvent, 30 bar H_2, 30 °C, 4 h.

producing selectively the alkene products. In case of the alkyne **1j** bearing a keto group in *para*-position on the aromatic ring both functionalities are reduced to the respective (*Z*)-1-(4-styrylphenyl) ethane-1-ol (**2j**) in 85% isolated yield. Attempts to shift the selectivity for this special substrate (**1j**) to the exclusive reduction of the triple bond failed. In fact, applying 1 mol% **Mn-3c** at 30 °C preferential reduction of the ketone took place. Furthermore, the heteroaromatic alkyne (**1r**) is converted in excellent yield (99%) and selectivity to the *cis*-olefin **2r**. In addition, the diyne **1t** is smoothly reduced on both triple bonds to the synthetically interesting (*Z*,*Z*)-diene **2t**. While the catalyst **Mn-3c** works efficiently for internal alkynes bearing at least one aromatic substituent, no conversion was detected for the



Scheme 1 Semihydrogenation of alkynes catalysed by **Mn-3c**. [a] Conversions are determined by GC analysis. Isolated yields are given in parentheses.

related alkyl-substituted internal alkyne **1u**. However, alkyne **1s** with an aromatic and aliphatic moiety smoothly reacted to the *cis*-olefin **2s**. Finally, three terminal alkynes **4a–c** were tested in the presence of 2 mol% **Mn-3c** at 30 bar hydrogen, 60 °C and 16 hours. Only the activated terminal alkyne **4c** was selectively reduced on the alkyne moiety giving 4-vinyl methylbenzoate **5c** in 76% isolated yield.

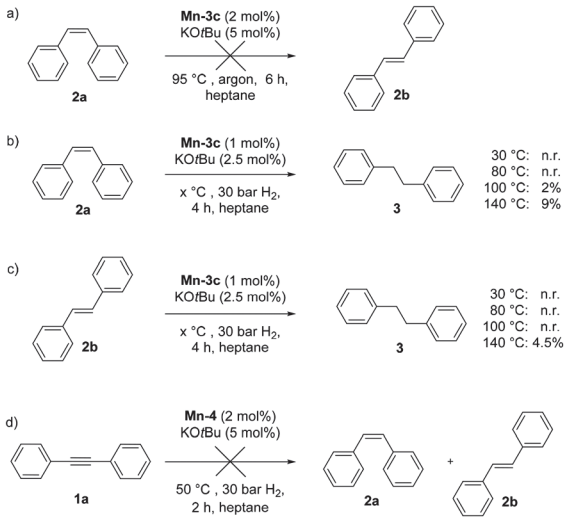
Investigation of the reaction mechanism

The reaction mechanism was studied based on both catalytic experiments and DFT computation. To investigate the potential isomerisation ability of our optimal catalyst system, *Z*-stilbene was heated with 2 mol% **Mn-3c** at 95 °C for 6 hours in the absence of hydrogen (Scheme 2a). Interestingly, no formation of the corresponding *E*-product was observed. This finding contrasts with the previous work of Milstein and co-workers, who reported isomerisation of the initially formed *Z*-product to the *E*-olefin with their acridine-based PNP iron complex **Fe-1**.[14a]

Besides, no isomerisation of **2** or reduction to 1,2-diphenylethane **3** was observed, when *cis*- or *trans*-stilbene were heated in the presence of 1 mol% of catalyst **Mn-3c** at 30 bar hydrogen pressure at 30 °C, 80 °C or 100 °C (Scheme 2b and c). At a temperature of 140 °C only little formation to the alkane occurred (9% of 1,2-diphenylethane **3**) potentially due to the fact that a major part of heptane and stilbene are in the gas phase, while the catalyst stays in the liquid phase. Nevertheless, these findings demonstrate the preference of **Mn-3c** for the hydrogenation of the triple bond compared to olefins and are in good agreement with theory *vide infra*. Here, the computations showed a slightly lower energy barrier for the hydrogenation of *cis*-stilbene (**2a:** 21.3 kcal mol^{-1}) to 1,2-diphenylethane than for *trans*-stilbene (**1b:** 23.2 kcal mol^{-1}).

Moreover, the so-called metal–ligand cooperation (MLC) was studied, which is often observed in catalytic hydrogenations with pincer complexes.[21] Also, in our previous works on catalytic reduction of carboxylic acid derivatives with iron,[22] cobalt[23] or manganese[18a,c] pincer complexes, the aliphatic PNP pincer ligand played an active role in the hydrogen transfer process.

To figure out the possible involvement of the pincer ligand in the direct hydrogenation of alkynes, a further control experiment was realised. To prove the ability of metal ligand cooperation, the NH moiety of the pincer backbone in the manganese catalyst was blocked with a methyl substituent.



Scheme 2 Mechanistic experiments for the semihydrogenation of alkynes. a) Isomerisation experiment with **Mn-3c**. b).

Therefore, the respective *N*-methylated manganese pincer complex **Mn-4** was synthesised starting from $[Mn(CO)_5Br]$ and pincer ligand $MeN(CH_2–CH_2–PEt_2)_2$ (see ESI†) and characterised by spectroscopic methods. The ^{31}P NMR spectra of **Mn-4** showed one signal at 64.6 ppm indicating the formation of only one isomer. Furthermore, in the IR-spectra two characteristic bands at 1899 and 1807 cm^{-1} are found in the carbonyl region demonstrating the presence of two CO molecules in the complex **Mn-4**. Signals at *m*/*z* 397 and *m*/*z* 415 were detected in the ESI-spectroscopic analysis referring to $[M(\textbf{Mn-4})–2CO]^+$ and $[M(\textbf{Mn-4})–Br + ACN]^+$, respectively. These fragments indicate the formation of the neutral manganese complex **Mn-4**. Additionally, a peak at *m*/*z* 402 was observed in trace amounts which could be assigned to a cationic Mn-species bearing three CO molecules and the pincer-backbone.

Such a similar coordination behaviour is known for the related **Mn-3c** complex, which forms the kinetically stable cationic **Mn-3ck** next to the thermodynamically more stable neutral compound **Mn-3c**, too.[18c] Finally, crystals suitable for X-ray diffraction analysis were grown in methanol solution stored at 0 °C. The molecular structure (Fig. 3) exhibited a distorted octahedral geometry.[24] Here, the manganese centre is surrounded by the PNP donor atoms of the pincer ligand and one CO molecule placed in an equatorial position and a bromine atom as well as a second CO molecule arranged in axial position. Taking all these analytical data into account the formation of the neutral Mn complex with the structure $[Mn(P^{Me}NP^{Et})(Br)(CO)_2]$ **Mn-4** is confirmed.

Using **Mn-4** for the model hydrogenation showed no conversion (Scheme 2d), which unambiguously proves the importance of the N–H moiety of the aliphatic ligand backbone. This experimental result also provides a strong hint for an outer-sphere hydrogenation mechanism in the catalytic reaction. This assumption was further explored by DFT computations. In our previous investigations on the hydrogenation of esters[18c] as well as nitriles, ketones and aldehydes[18a] using the same type of catalysts (**Mn-3**) (Fig. 1) an outer-sphere hydrogenation mechanism was proposed, too. In more detail, the Mn–H transfer step with the formation of an intermediate and a subsequent N–H transfer to the product could be verified by experiment and theory. Furthermore, such aliphatic Mn pincer based catalysts have been successfully used in the isomerisation of allylic alcohols to the corresponding carbonyl compounds *via* a dehydrogenation/hydrogenation pathway, which was validated by the isolation of an intermediate, deuterium labelling experiments as well as by comparative DFT computation.[25] A similar outer-sphere mechanism has been discussed for the hydrogenation of quinolines by using well-defined PNP and PNN pincer manganese complexes.[26]

Therefore, the hydrogenated complex **Mn-3ca**, which should be involved in the catalytic cycle, was prepared separately by treating **Mn-3c** with 2 equivalents of $NaBEt_3H$ (1 M in THF) for 24 hours at room temperature. This complex was isolated from a red solution giving a brown oil, which was not stable in pure form. Therefore, **Mn-3ca** was handled in a stock solution, which was used to confirm the structure by spectroscopic methods. In the ^1H NMR spectrum characteristic peaks for the hydride group were found at −5.8 and −6.1 ppm. During the MS analysis signals at *m*/*z* 360 and 401 were detected, which can be assigned to $[M(\textbf{Mn-3ca})–H]^+$ and $[M(\textbf{Mn-3ca})–H + ACN]^+$ (see ESI† for further details). Using 2 mol% of **Mn-3ca** for the benchmark reaction provided *cis*-stilbene in 85% yield (Table 2, entry 13) only in the presence of 5 mol% KO*t*Bu. Interestingly, the hydride species **Mn-3ca** is not active without base (Table 2, entry 14). A possible reason for this catalytic behaviour is the preferential formation of the thermodynamically more stable *trans*-**Mn-3ca** isomer during the synthesis, which is confirmed by DFT computation and NMR analysis (see ESI†).[27] As an outer-sphere mechanism is discussed, in case of a *trans*-**Mn-3ca** complex no concerted hydride transfer from the catalyst to the substrate is possible. In order to form the active *cis*-configuration, the base is needed to generate the amido complex **Mn-3cb**, which then forms the *cis*-**Mn-3ca** under a hydrogen atmosphere (Scheme 3).

Considering all these findings and the performed experimental work, the hydrogenation of 1,2-diphenylethyne **1a** was computed on the basis of such a bifunctional outer-sphere mechanism (Scheme 4, top).

Extensive benchmark calculations including different functional methods in gas-phase as well as in solution (SMD[28]) with van der Waals dispersion correction (GD3BJ[29]) were carried out on the basis of the real-size catalysts (ethyl-substituted PNP ligand) and substrates in order to select the appropriate computational methods. In the following the

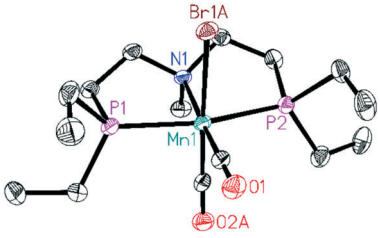
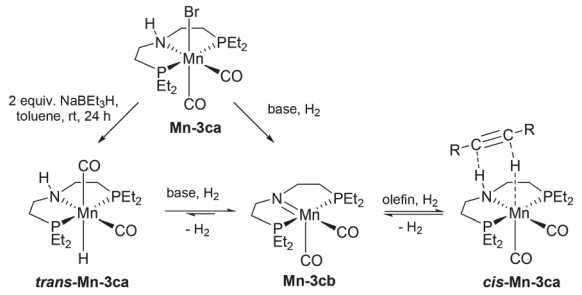
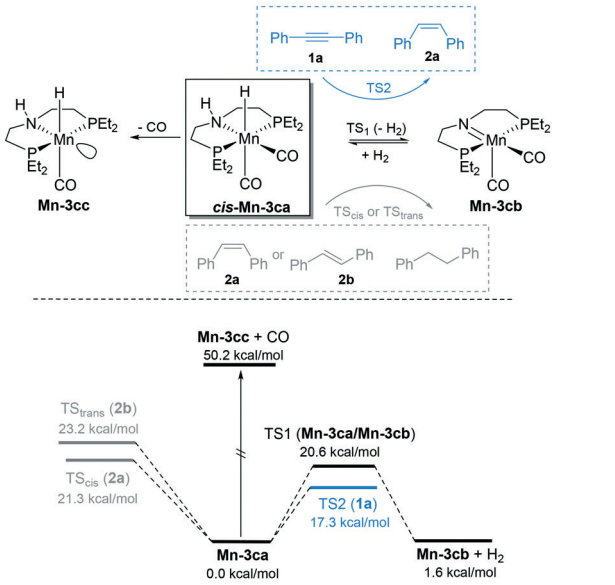


Fig. 3 Molecular structure of **Mn-4** in the crystal. Only one molecule of the asymmetric unit is depicted. Displacement ellipsoids correspond to 30% probability. Hydrogen atoms and atoms of lower occupancy are omitted for clarity; for further information see ESI.†



Scheme 3 Postulated formation of *cis*- and *trans*-**Mn-3ca**.



Scheme 4 Proposed bifunctional outer-sphere mechanism for the Mn-catalysed hydrogenation of alkyne 1a and alkenes 2 (top) and M06L/6-311+G(3df,3pd) computed Gibbs free energy in heptane solution (bottom)

data from M06L[30] in combination with the all electron 6-311++G(3df,3pd) basis set[31] in heptane solution are presented (Scheme 4, bottom). Other results are given in the ESI.† For hydrogenation reactions, a stepwise reaction scheme has been calculated, where the first Mn–H transfer has a higher barrier than the second N–H transfer.[32] Therefore, only the simplified potential free energy surface with only the highest barriers (the Mn–H transfer step) is discussed. In agreement with previous results,[18] the interconversion from the hydride **Mn-3ca** to the amido complex **Mn-3cb** has a Gibbs free energy barrier of 20.6 kcal mol^{-1} and is slightly endergonic (1.6 kcal mol^{-1}) revealing adjustable reversibility and equilibrium under given conditions. In addition, the CO dissociation to **Mn-3cc** is highly endergonic by 50.2 kcal mol^{-1} demonstrating an enhanced stability of complex **Mn-3ca**.

The hydrogenation of 1,2-diphenylethyne (**1a**) to *cis*-stilbene (**2a**) has a free energy barrier of 17.3 kcal mol^{-1}, which is lower than that (20.6 kcal mol^{-1}) of H_2 elimination and is exergonic by 24.4 kcal mol^{-1}. Both values indicate that in case of the hydrogenation reaction the energy barrier is lower. These findings agree with the experimental results, where the hydrogenation of 1,2-diphenylethyne (**1a**) to *cis*-stilbene (**2a**) is accessible at low temperature and low H_2 pressure (Table 1, entries 14–18).

Furthermore, the corresponding hydrogenation of *cis*- (**2a**) and *trans*-stilbene (**1b**) to 1,2-diphenylethane (Scheme 2b and c) was computed to have barrier of 21.3 and 23.2 kcal mol^{-1}, and exergonic reaction free energy by 18.9 and 13.1 kcal mol^{-1}, respectively. In comparison with the free energy barrier of H_2 elimination, the hydrogenation of *cis*- and *trans*-stilbene requires higher temperature and/or higher H_2 pressure. Such high pressure is necessary to keep the stability of complex **Mn-3ca** towards H_2 elimination, especially in case of *trans*-stilbene hydrogenation. The higher barrier of the hydrogenation of *cis*- and *trans*-stilbene compared to the hydrogenation of 1,2-diphenylethyne explains the observed chemoselectivity as well as the inactivity of *cis*- and *trans*-stilbene up to 100 °C (Scheme 2b and c). Under the optimized conditions for the semihydrogenation of 1,2-diphenylethyne (**1a**), neither *cis*-stilbene nor *trans*-stilbene can be hydrogenated further on. However, at elevated temperature of 140 °C and 30 bar H_2 pressure, slow transformation of *cis*- and *trans*-stilbene into the corresponding alkane was found. As the energy barriers of the interconversion of the active catalysts between **Mn-3ca** and **Mn-3cb** are close to the hydrogenation barriers of *cis*- and *trans*-stilbene, one could expect that the reaction should occur at high temperature. The observed low reactivity might be associated with the reduced solubility of H_2 gas in solution at high temperature,[33] as well as with the crossover of the reaction to the gas phase.

DFT computation is also a helpful tool to understand the reaction behaviour of different substituted alkynes (Scheme 1): thus, in substrate **1j** the preferential hydrogenation of the ketone group can be explained by the lower hydrogenation barrier of benzophenone (15.5 kcal mol^{-1}) compared to the hydrogenation barrier of the alkyne functionality in 1,2-diphenylacetylene (**1a**). On the other side, for methyl 4-(phenylethynyl)benzoate (**1i**) a barrier of 22.2 kcal mol^{-1} was computed for the first hydrogenation step of methyl benzoate (Ph–$COOCH_3$), which is higher than that of C≡C triple bond hydrogenation of **1a**. Therefore, a high chemoselectivity for the hydrogenation of alkyne moiety was observed in **1i**.

Also, the strong influence of the alkyl substitution on the reactivity of alkynes can be elucidated by DFT computations. While alkyne **1s** with one phenyl and one alkyl substituent can be smoothly reduced, 4-octyne (**1u**) bearing two alkyl groups showed no activity at all. This effect is caused by the high energy barrier in case of alkyl substitution. Here, a barrier of 26.7 kcal mol^{-1} was computed for the hydrogenation of 4-octyne (**1u**), which is by 9.4 kcal mol^{-1} higher than that of **1a** hydrogenation. All these values clearly explain and support the experimental results.

Conclusions

For the first time the selective hydrogenation of alkynes using hydrogen in the presence of molecularly defined manganese pincer complexes is described. Specifically, the manganese complex **Mn-3c** coordinated by an aliphatic PNP pincer ligand allows for highly chemo- and stereoselective semihydrogenation of internal alkynes under mild conditions. Moreover, this non-noble metal derived pre-catalyst efficiently converts various internal alkynes to the corresponding *Z*-olefins. Mechanistic investigations based on experiments and computations reveal a direct involvement of

the pincer ligand in the hydrogenation step *via* an outer sphere pathway.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank Dr. C. Fischer, S. Buchholz, S. Schareina (all LIKAT) for their excellent analytical support. The authors thank Bianca Tannert for their excellent technical assistance in the laboratory. This work was supported by the State of Mecklenburg-Western Pomerania and the BMBF.

Notes and references

1 J. G. de Vries and C. J. Elsevier, in *Handbook of Homogeneous Hydrogenation*, Wiley-VCH, Weinheim, 2007.

2 (*a*) P. N. Rylander, in *Catalytic Hydrogenation in Organic Syntheses*, Academic Press, New York, 1979; (*b*) P. G. Andersson and I. J. Munslow, in *Modern Reduction Methods*, Wiley, New York, 2008; (*c*) C. Oger, L. Balas, T. Durand and J.-M. Galano, *Chem. Rev.*, 2013, **113**, 1313–1350.

3 (*a*) H. Lindlar, *Helv. Chim. Acta*, 1952, **35**, 446–450; (*b*) H. Lindlar and R. Dubuis, *Org. Synth.*, 1966, **46**, 89; (*c*) B. M. Trost and R. Braslau, *Tetrahedron Lett.*, 1989, **30**, 4657–4660; (*d*) A. Bacchi, M. Carcelli, M. Costa, A. Leporati, E. Leporati, P. Pelagatti, C. Pelizzi and G. Pelizzi, *J. Organomet. Chem.*, 1997, **535**, 107–120; (*e*) P. Pelagatti, A. Venturini, A. Leporati, M. Carcelli, M. Costa, A. Bacchi, G. Pelizzi and C. Pelizzi, *J. Chem. Soc., Dalton Trans.*, 1998, 2715–2721; (*f*) C. A. Hamilton, S. D. Jackson, G. J. Kelly, R. Spence and R. D. de Bruin, *Appl. Catal., A*, 2002, **237**, 201–209; (*g*) L. L. Wei, L. M. Wei, W. B. Pan, S. P. Leou and M. J. Wu, *Tetrahedron Lett.*, 2003, **44**, 1979–1981.

4 (*a*) R. R. Schrock and J. A. Osborn, *J. Am. Chem. Soc.*, 1976, **98**, 2143–2147; (*b*) C. Kohrt, G. Wienhöfer, C. Pribbenow, M. Beller and D. Heller, *ChemCatChem*, 2013, **5**, 2818–2821; (*c*) S. Furukawa, A. Yokoyama and T. Komatsu, *ACS Catal.*, 2014, **4**, 3581–3585; (*d*) J. Luo, R. Theron, L. J. Sewell, T. N. Hooper, A. S. Weller, A. G. Oliver and J. S. McIndoe, *Organometallics*, 2015, **34**, 3021–3028; (*e*) S. A. Jagtap and B. M. Bhanage, *ChemistrySelect*, 2018, **3**, 713–718; (*f*) S. P. Desai, J. Ye, J. Zheng, M. S. Ferrandon, T. E. Webber, A. E. Platero-Prats, J. Duan, P. Garcia-Holley, D. Camaioni, K. W. Chapman, M. Delferro, O. K. Farha, J. L. Fulton, L. Gagliardi, J. A. Lercher, R. L. Penn, A. Stein and C. C. Lu, *J. Am. Chem. Soc.*, 2018, **140**, 15309–15318; (*g*) S. P. Desai, J. Ye, T. Islamoglu, O. K. Farha and C. C. Lu, *Organometallics*, 2019, **38**, 3466–3473.

5 (*a*) Y. Shvo, I. Goldberg, D. Czerkie, D. Reshef and Z. Stein, *Organometallics*, 1997, **16**, 133–138; (*b*) J. Li and R. Hua, *Chem. – Eur. J.*, 2011, **17**, 8462–8465; (*c*) Y. Yamamoto, S. Mori and M. Shibuya, *Chem. – Eur. J.*, 2013, **19**, 12034–12041; (*d*) K. Radkowski, B. Sundararaju and A. Fürstner, *Angew. Chem., Int. Ed.*, 2013, **52**, 355–360; (*e*) M. Leutzsch, L. M. Wolf, P. Gupta, M. Fuchs, W. Thiel, C. Farès and A. Fürstner, *Angew. Chem., Int. Ed.*, 2015, **54**, 12431–12436; (*f*) S. Musa, A. Ghosh, L. Vaccaro, L. Ackermann and D. Gelman, *Adv. Synth. Catal.*, 2015, **357**, 2351–2357; (*g*) K. T. Neumann, S. Klimczyk, M. N. Burhardt, B. Bang-Andersen, T. Skrydstrup and A. T. Lindhardt, *ACS Catal.*, 2016, **6**, 4710–4714; (*h*) R. Kusy and K. Grela, *Org. Lett.*, 2016, **18**, 6196–6199; (*i*) A. Guthertz, M. Leutzsch, L. M. Wolf, P. Gupta, S. M. Rummelt, R. Goddard, C. Fares, W. Thiel and A. Fürstner, *J. Am. Chem. Soc.*, 2018, **140**, 3156–3169.

6 T. L. Gianetti, N. C. Tomson, J. Arnold and R. G. Bergman, *J. Am. Chem. Soc.*, 2011, **133**, 14904–14907.

7 M. Sodeoka and M. Shibasaki, *J. Org. Chem.*, 1985, **50**, 1147–1149.

8 H. S. La Pierre, J. Arnold and F. D. Toste, *Angew. Chem., Int. Ed.*, 2011, **50**, 3900–3903.

9 C. Oger, L. Balas, T. Durand and J. Galano, *Chem. Rev.*, 2013, **113**, 1313–1350.

10 (*a*) F. Alonso, M. Osante and M. Yus, *Adv. Synth. Catal.*, 2006, **348**, 305–308; (*b*) R. Barrios-Francisco and J. J. Garcia, *Inorg. Chem.*, 2009, **48**, 386–393; (*c*) T. Chen, J. Xiao, Y. Zhou, S. Yin and L. Han, *J. Org. Chem.*, 2014, **749**, 51–54; (*d*) E. Richmond and J. Moran, *J. Org. Chem.*, 2015, **80**, 6922–6929; (*e*) H. Konnerth and M. H. G. Prechtl, *Chem. Commun.*, 2016, **52**, 9129–9132; (*f*) X. Wen, X. Shi, X. Qiao, Z. Wu and G. Bai, *Chem. Commun.*, 2017, **53**, 5372–5375; (*g*) M. D. de los Bernardos, S. Pérez-Rodríguez, A. Gual, C. Claver and C. Godard, *Chem. Commun.*, 2017, **53**, 7894–7897; (*h*) K. Murugesan, A. S. Alshammari, M. Sohail, M. Beller and R. V. Jagadeesh, *J. Catal.*, 2019, **370**, 372–377.

11 (*a*) C. Chen, Y. Huang, Z. Zhang, X.-Q. Dong and X. Zhang, *Chem. Commun.*, 2017, **53**, 4612–4615; (*b*) F. Chen, C. Kreyenschulte, J. Radnik, H. Lund, A.-E. Surkus, K. Junge and M. Beller, *ACS Catal.*, 2017, **7**, 1526–1532.

12 (*a*) C. Bianchini, A. Meli, M. Peruzzini, F. Vizza, F. Zanobini and P. Frediani, *Organometallics*, 1989, **8**, 2080–2082; (*b*) C. Bianchini, A. Meli, M. Peruzzini, P. Frediani, C. Bohanna, M. A. Esteruelas and L. A. Oro, *Organometallics*, 1992, **11**, 138–145; (*c*) S. C. Bart, E. Lobkovsky and P. J. Chirik, *J. Am. Chem. Soc.*, 2004, **126**, 13794–13807; (*d*) G. Wienhöfer, F. A. Westerhaus, R. V. Jagadeesh, K. Junge, H. Junge and M. Beller, *Chem. Commun.*, 2012, **48**, 4827–4829; (*e*) T. N. Gieshoff, A. Welther, M. T. Kessler, M. H. G. Prechtl and A. Jacobi von Wangelin, *Chem. Commun.*, 2014, **50**, 2261–2264; (*f*) L. C. Misal Castro, H. Li, J.-B. Sortais and C. Darcel, *Green Chem.*, 2015, **17**, 2283–2303; (*g*) D. Wei and C. Darcel, *Chem. Rev.*, 2019, **119**, 2550–2610; (*h*) B. J. Gregori, F. Schwarzhuber, S. Pöllath, J. Zweck, L. Fritsch, R. Schoch, M. Bauer and A. Jacobi von Wangelin, *ChemSusChem*, 2019, **12**, 3864–3870; (*i*) W. D. Jones, in *Topic in Organometallic Chemistry*, 2019, vol. 63, pp. 141–174.

13 (*a*) A. M. Whittaker and G. Lalic, *Org. Lett.*, 2013, **15**, 1112–1115; (*b*) A. Fedorov, H.-J. Liu, H.-K. Lo and C. Copéret, *J. Am. Chem. Soc.*, 2016, **138**, 16502–16507; (*c*) T. Wakamatsu, K. Nagao, H. Ohmiya and M. Sawamura, *Organometallics*, 2016, **35**, 1354–1357; (*d*) N. Kaeffer, H.-J. Liu, H.-K. Lo, A. Fedorov and C. Copéret, *Chem. Sci.*, 2018, **9**, 5366–5371.

14 (*a*) D. Srimani, Y. Diskin-Posner, Y. Ben-David and D. Milstein, *Angew. Chem.*, 2013, **125**, 14131–14134 (*Angew. Chem., Int. Ed.*, 2013, **52**, 14381–14384); (*b*) N. Gorgas, J. Brünig, B. Stöger, S. Vanicek, M. Tilset, L. F. Veiros and K. Kirchner, *J. Am. Chem. Soc.*, 2019, **141**, 17452–17458.

15 (*a*) K. Tokmic and A. R. Fout, *J. Am. Chem. Soc.*, 2016, **138**, 13700–13705; (*b*) S. Fu, N.-Y. Chen, X. Liu, Z. Shao, S. P. Luo and Q. Liu, *J. Am. Chem. Soc.*, 2016, **138**, 8588–8594; (*c*) V. G. Landge, J. Pitchaimani, S. P. Midya, M. Subaramanian, V. Madhu and E. Balaraman, *Catal. Sci. Technol.*, 2018, **8**, 428–433; (*d*) X. Qi, X. Liu, L.-B. Qu, Q. Liu and Y. Lan, *J. Catal.*, 2018, **362**, 25–34. For hydroboration of alkynes with Co pincer catalysts, see: (*e*) J. V. Obligacion, J. M. Neely, A. N. Yazdani, I. Pappas and P. J. Chirik, *J. Am. Chem. Soc.*, 2015, **137**, 5855–5858; (*f*) J. Guo, B. Cheng, X. Shen and Z. Lu, *J. Am. Chem. Soc.*, 2017, **139**, 15316–15319. For hydrosilylation of alkynes with Co pincer catalysts, see: (*g*) J. Guo and Z. Lu, *Angew. Chem., Int. Ed.*, 2016, **55**, 10835–103838.

16 K. Murugesan, C. Beromeo Bheeter, P. R. Linnebank, A. Spannenberg, J. N. H. Reek, R. V. Jagadeesh and M. Beller, *ChemSusChem*, 2019, **12**, 3363–3369.

17 (*a*) Y.-P. Zhou, Z. Mo, M.-P. Luecke and M. Driess, *Chem. – Eur. J.*, 2018, **24**, 4780–4784; (*b*) A. Brzozowska, L. M. L. Azofra, V. Zubar, I. Atodiresei, L. Cavallo, M. Rueping and O. El-Sepelgy, *ACS Catal.*, 2018, **8**, 4103–4109.

18 (*a*) S. Elangovan, C. Topf, S. Fischer, H. Jiao, A. Spannenberg, W. Baumann, R. Ludwig, K. Junge and M. Beller, *J. Am. Chem. Soc.*, 2016, **138**, 8809–8814; (*b*) S. Elangovan, J. Neumann, J.-B. Sortais, K. Junge, C. Darcel and M. Beller, *Nat. Commun.*, 2016, **7**, 12641; (*c*) S. Elangovan, M. Garbe, K. Junge, H. Jiao, A. Spannenberg and M. Beller, *Angew. Chem., Int. Ed.*, 2016, **56**, 15364–15368; (*d*) M. Andérez-Fernández, L. K. Vogt, S. Fischer, W. Zhou, H. Jiao, M. Garbe, S. Elangovan, K. Junge, H. Junge, R. Ludwig and M. Beller, *Angew. Chem., Int. Ed.*, 2017, **56**, 559–562.

19 V. Papa, J. R. Cabrero-Antonino, E. Alberico, A. Spannenberg, H. Junge, K. Junge and M. Beller, *Chem. Sci.*, 2017, **8**, 3576–3585.

20 (*a*) M. Perez, S. Elangovan, H. Jiao, A. Spannenberg, K. Junge and M. Beller, *ChemSusChem*, 2017, **10**, 83–86; (*b*) S. Budweg, K. Junge and M. Beller, *Chem. Commun.*, 2019, **55**, 14143–14146.

21 J. R. Khusnutdinova and D. Milstein, *Angew. Chem.*, 2015, **127**, 12406–12445 (*Angew. Chem., Int. Ed.*, 2015, **54**, 12236–12273).

22 (*a*) C. Bornschein, S. Werkmeister, B. Wendt, H. Jiao, E. Alberico, W. Baumann, H. Junge, K. Junge and M. Beller, *Nat. Commun.*, 2014, **5**, 4111; (*b*) S. Lange, S. Elangovan, C. Cordes, A. Spannenberg, H. Jiao, H. Junge, S. Bachmann, M. Scalone, C. Topf, K. Junge and M. Beller, *Catal. Sci. Technol.*, 2016, **6**, 4768–4772.

23 (*a*) K. Junge, B. Wendt, A. Cingolani, A. Spannenberg, Z. Wei, H. Jiao and M. Beller, *Chem. – Eur. J.*, 2018, **24**, 1046–1052; (*b*) J. Schneekönig, B. Tannert, H. Hornke, M. Beller and K. Junge, *Catal. Sci. Technol.*, 2019, **9**, 1779–1783.

24 Deposition number 1980954 contains the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service www.ccdc.cam.ac.uk/structures.

25 (*a*) K. Singh Rawata and B. Pathak, *Catal. Sci. Technol.*, 2017, **7**, 3234–3242; (*b*) T. Xia, B. Spiegelberg, Z. Wei, H. Jiao, S. Tin, S. Hinze and J. G. de Vries, *Catal. Sci. Technol.*, 2019, **9**, 6327–6334.

26 Y. Wang, L. Zhu, Z. Shao, G. Li, Y. Lan and Q. Liu, *J. Am. Chem. Soc.*, 2019, **141**, 17337–17349.

27 The *trans* isomer is more stable than the *cis* isomer by 1.5 kcal mol^{-1}, which gives a thermodynamic ratio of 93/7.

28 A. V. Marenich, C. J. Cramer and D. G. Truhlar, *J. Phys. Chem. B*, 2009, **113**, 6378–6396.

29 S. Grimme, S. Ehrlich and L. Goerigk, *J. Comput. Chem.*, 2011, **32**, 1456–1465.

30 Y. Zhao and D. G. Truhlar, *J. Chem. Phys.*, 2006, **125**, 194101.

31 M. J. Frisch, J. A. Pople and J. S. Binkley, *J. Chem. Phys.*, 1984, **80**, 3265–3269.

32 (*a*) Z. Wei, A. de Aguirre, K. Junge, M. Beller and H. Jiao, *Eur. J. Inorg. Chem.*, 2018, 4643–4657; (*b*) Z. Wei, A. de Aguirre, K. Junge, M. Beller and H. Jiao, *Catal. Sci. Technol.*, 2018, **8**, 3649–3665; (*c*) Z. Wei and H. Jiao, *Adv. Inorg. Chem.*, 2019, **73**, 323–384.

33 E. Brunner, *J. Chem. Eng. Data*, 1985, **30**, 269–273.

10 Appendix

10.1 Further Publications

The publication (see below, chapter 10.1.1), which was mainly prepared during my master studies, builds the basis of the publication 9.1 and is therefore presented in this chapter as additional information for the readers convenience. The review (chapter 10.1.2) was prepared during my PhD.

10.1.1 Manganese(I)-catalysed Enantioselective Hydrogenation of Ketones Using a Defined Chiral PNP Pincer Ligand

M. Garbe, K. Junge, S. Walker, Z. Wei, H. Jiao, A. Spannenberg, S. Bachmann, M. Scalone and M. Beller

Angew.Chem. Int. Ed. **2017**, *56*, 11237–11241.

International Edition: DOI: 10.1002/anie.201705471
German Edition: DOI: 10.1002/ange.201705471

10.1.2 Catalytic oxidations by dehydrogenation of alkanes, alcohols and amines with defined (non)-noble metal pincer complexes

S. Budweg, K. Junge and M. Beller

Catal. Sci. Technol. **2020**, *10*, 3825–3842.

DOI: 10.1039/D0CY00699H

10.2 Curriculum Vitae

Personal Data

Name	Svenja Budweg (née Walker)
Date and place of birth	08.01.1990 in Ravensburg

Education

04/2018 – Today	**Research assistant – Dr. rer. nat. der Chemie** *Leibniz-Institut für Katalyse* *University of Rostock* Chair of Homogeneous Catalysis - Prof. Dr. Matthias Beller Title: Manganese- and Iron-Catalysed (De)Hydrogenations
04/2016 – 03/2018	**Master of Science (M.Sc.) – Chemistry** *University of Rostock* Master thesis: *Leibniz-Institut für Katalyse* Chair of Homogeneous Catalysis - Prof. Dr. Matthias Beller Title: Dehydrierung von Alkoholen mit Pincer-Komplexen
10/2012 – 02/2016	**Bachelor of Science (B.Sc.) – Chemistry** *University of Rostock* Bachelor thesis: Chair of Inorganic Chemistry - Prof. Dr. Axel Schulz Title: Einführung der Triphenylsilylgruppe als sterisch anspruchsvoller Rest in der PN-Chemie
10/2009 – 08/2012	**Teacher Training Studies for Chemistry and Geography** *University of Würzburg*
09/2000 – 05/2009	**Abitur (A-levels)** *Deutschhaus-Gymnasium Würzburg* Intensive courses: Chemistry, English

09/2000 – 05/2009	**Abitur (A-levels)** *Deutschhaus-Gymnasium Würzburg* Intensive courses: Chemistry, English

Work Experience

10/2018 – 02/2019	**Student assistant** *University of Rostock* Faculty for Agricultural and Environmental Sciences Lecture/Tutorial "*Allgemeine Chemie für Agrarwissenschaftler*"
06/2017 – 09/2017	**Research Trainee** *Bayer Pharmaceuticals, Wuppertal* Drug synthesis: Organic chemistry; analytics
11/2015 – 11/2016	**Research Associate** *Leibniz-Institut für Katalyse* Chair of Homogeneous Catalysis - Prof. Dr. Matthias Beller Synthesis of pincer ligands
08/2015 – 10/2015	**Trainee** *LUFA GmbH - Landwirtschaftliche Untersuchungs- und Forschungsanstalt (LMS Agrarberatung), Rostock* Analytics of soil, water, and fertiliser samples DIN EN ISO/IEC 17025
02/2015 – 02/2016	**Student assistant** *University of Rostock* Chair of Inorganic Chemistry - Prof. Dr. Axel Schulz Control of internship reports

10.3 List of publications

M. Garbe, K. Junge, S. Walker, Z. Wei, H. Jiao, A. Spannenberg, S. Bachmann, M. Scalone, M. Beller, *Angew. Chem. Int. Ed*., **2017**, *56*, 11237–11241.

S. Budweg, Z. Wei, H. Jiao, K. Junge, M. Beller, *ChemSusChem*, **2019**, *12*, 2988–2993.

S. Budweg, K. Junge, Matthias Beller, *Chem. Commun.*, **2019**, *55*, 14143–14146.

M.Garbe, S. Budweg, V. Papa, Z. Wei, H. Hornke, S. Bachmann, M. Scalone, A. Spannenberg, H. Jiao, K. Junge, M. Beller, *Catal. Sci. Technol.*, **2020**, *10*, 3994–4001.

S. Budweg, K. Junge, M. Beller, *Catal. Sci. Technol.*, **2020**, *10*, 3825–3842.

K. Blaesing, R. Labbow, D. Michalik, F. Reiß, A. Schulz, A. Villinger, S. Walker, *Chem. – Eur. J.*, **2020**, *26*, 1640–1652.

10.4 Conference participations

1) Poster: “Iron PNP-Pincer-catalyzed Transfer-Dehydrogenation of Secondary Alcohols”, S. Budweg, Z. Wei, H. Jiao, K. Junge, M. Beller, *21st JCF-Frühjahrssymposium*, Bremen, March **2019**.

2) Poster: “Transfer-Dehydrogenation of Secondary Alcohols Catalyzed by Manganese NNN-Pincer Complexes”, S. Budweg, K. Junge, M. Beller, *53st German Catalysis Meeting*, Weimar, March **2020**, cancellation due to Corona pandemic.