Alkylated PTA platforms for mono- and polynuclear pre-catalysts for the aqueous biphasic hydroformylation of 1-octene

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By

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A dissertation submitted in fulfilment of the requirement of the degree

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Plagiarism declaration

I know the meaning of plagiarism and I declare that "**Alkylated PTA platforms for mono- and polynuclear pre-catalysts for the aqueous biphasic hydroformylation of 1-octene**" is my own work and has never, to the best of my knowledge, been reported or submitted for any degree or examination by any university. All Sources of information used are cited and completely referenced at the end of each chapter.

Signed by candidate

Diteboho Ramarou

29 / 11 / 2017

Date

Dedication

This dissertation is dedicated to my late mother Nkemeleng Ramarou with love.

Acknowledgements

Firstly, I would like to thank God for the gift of life, the blessings and grace bestowed upon me to carry out this work.

Secondly, I would like to express my utmost gratitude to my supervisors, Associate Professor Gregory Smith and Dr Banothile Makhubela for their guidance, encouragement and support throughout this project.

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Conference/Symposium Contributions

November 2016 – Poster Presentation

Alkylated PTA platforms for mono- and polynuclear aqueous phase hydroformylation catalysts. Catalysis Society of South Africa (CATSA) conference; Central Drakensberg.

August 2017 – Poster Presentation

The hydroformylation of 1-octene using mono- and polynuclear Rh/PTA pre-catalysts. 10th Annual Science Postgraduate Student Council Symposium; University of Cape Town.

August 2017 – Poster Presentation

Alkylated PTA platforms as mono- and polynuclear pre-catalysts for the hydroformylation of 1-octene. 6th International Conference for Young Chemists; Penang, Malaysia.

November 2017 – Poster Presentation

The application of water-soluble Rh-PTA complexes as pre-catalysts in the aqueous biphasic catalysis of 1-octene. Catalysis Society of South Africa (CATSA) conference; Pilanesberg National Park.

Awards

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Abstract

A series of mono-, di- and trimeric alkylated PTA ligands were synthesised. These ligands were reacted with the dimeric rhodium precursor, $[RhCl(COD)]_2$, to produce the corresponding mono-, di- and trinuclear Rh(I)-PTA complexes. These complexes were then reacted with carbon monoxide to substitute the COD ligands with CO ligands, yielding the carbonyl analogues of the complexes. The ligands and complexes were fully characterised using various spectroscopic and analytical techniques, which include ^{1}H, ^{13}C and ^{31}P NMR spectroscopy, FT-IR spectroscopy, mass spectrometry, and elemental analysis. The ligands were found to have good solubility in water at room temperature, while the complexes showed water solubility at elevated temperatures. All the complexes were evaluated as catalyst precursors in the aqueous biphasic hydroformylation of 1-octene.

The hydroformylation reactions showed that the complexes (**6** – **18**) were all active when used as catalyst precursors in the aqueous biphasic hydroformylation of 1-octene to yield aldehydes (linear and branched) and iso-octenes as side products. All complexes exhibited good chemoselectivity for aldehydes with the COD complexes displaying better chemoselectivity towards aldehydes than the CO complexes. However, the CO complexes exhibited better regioselectivity for linear aldehydes than the COD complexes. The trinuclear complex displayed accelerated catalytic rates than the dinuclear complexes which, in turn, displayed faster rates than the mononuclear complexes.

The complexes could be recycled three times with a marked decrease in the conversion of 1-octene after each run for each catalyst precursor. Leaching studies showed a significant loss of the metal catalysts into the organic layer after each catalytic run.

Mercury poisoning studies were conducted and confirmed that, under the catalytic conditions, all complexes behaved entirely as homogeneous catalysts when evaluated as catalyst precursors for the aqueous biphasic hydroformylation of 1-octene.

List of Abbreviations

º	degrees
ºC	degrees celsius
δ	chemical shift
ν	wavenumber
AB q	AB quartet
acac	acetylacetonate
Ar	aromatic
bmim	1-butyl-3-methylimidazolium
br s	broad signal
^{13}C NMR	carbon-13 nuclear magnetic resonance
Calcd.	calculated
cm^{-1}	reciprocal centimetres
CO	carbonyl or carbon monoxide
COD	1,5-cyclooctadiene
d	doublet
DCM	dichloromethane
dd	doublet of doublets
DMSO	dimethyl sulfoxide
ESI-MS	electrospray ionisation mass spectrometry
FIL	fuctionalised ionic liquid
FT-IR	Fourier transform infrared spectroscopy
GC	gas chromatography

^{1}H NMR	proton nuclear magnetic resonance
HSQC	heteronuclear single quantum correlation
Hz	hertz
ICP-OES	inductively coupled plasma optical emission spectrometry
IL	ionic liquid
IR	Infrared
J	coupling constant
LC-MS	liquid chromatography mass spectrometry
m	multiplet
m.p.	melting point
mg	milligram(s)
mL	milliliter(s)
mmol	millimole(s)
m/*z*	mass to charge ratio
NMR	nuclear magnetic resonance
^{31}P NMR	phosphorus nuclear magnetic resonance
PF_6	hexaflurophosphate
PPh_3	triphenylphosphine
ppm	parts per million
PTA	1,3,5-triaza-7-phosphaadamantane
q	quartet
r.t.	room temperature
rac	racemic

s	singlet (NMR) or strong (IR)
$S_{20°C}$	solubility at room temperature
$S_{40°C}$	solubility at 40 °C
$scCO_2$	supercritical carbon dioxide
syngas	synthesis gas
t	triplet
TOF	turnover frequency
TON	turnover number
TPPMS	monosulfonated triphenylphosphine
TPPTS	triphenylphosphine trisulfonate

Chapter 1

Literature review

1.1 Catalysis

Catalysis is a process that has been used since the 18th century, although initially its theory and characteristics were not fully understood.[1] Catalysis now plays a very important role in the chemical industry and is fundamental to the production of a large number of value-added chemicals.[2] Catalysts aid in the manufacture of over 90% of all the industrial chemicals produced.[3] As a result, catalysis has grown to be the most significant field of research in areas such as organometallic chemistry, chemical engineering and material science.[4] Catalysts have the ability to initiate reactions by combining two or more molecular fragments, with most or all the atoms from the initial fragments making up the product.[5] Furthermore, the use of catalysts is advantageous in a number of ways including lowering energy requirements, increasing selectivity, reducing processing and separating agents and using less toxic materials and catalytic amounts as opposed to stoichiometric amounts.[6,7]

Catalysis by transition metal complexes has been extensively studied, due to the fact that the properties of transition metals can be changed easily by coordinating appropriate ligands to give the desired coordination complexes.[8] The choice of metal and ligand combination can prove beneficial for the improvement of the stability, activity and selectivity of the catalyst.[9]

New catalysts are designed in an attempt to improve features such as the turnover number, the stability of the catalyst during the catalytic reaction, the solubility of the catalyst in the desired reaction medium and catalyst recovery.[5,6] With the abundance of feedstocks such as alkanes and alkenes, there is a requirement for the design and synthesis of new catalysts which are more efficient for the conversion of the alkanes and alkenes into more useful products like aldehydes.[10,11] The study and use of transition metals both in catalysis and medicine is being vastly explored.[12,13]

There are two different types of catalytic systems, heterogeneous and homogeneous catalysis. The main distinguishing feature of the two systems is the phase of the catalyst during a catalytic reaction.[9] Heterogeneous catalysts are in a phase different from the substrates and products, which implies that only the surface of the catalyst is available for the catalytic reaction.[14] Conversely, homogeneous catalysts are dissolved in the same media as the substrates and products and as a result all catalytic sites are accessible for the reaction.[15]

Heterogeneous catalysts are usually metals or metal oxides supported on solid supports such as silica and alumina.[14] Heterogeneous catalysts are more stable at high temperatures and pressures compared to most homogeneous catalysts. One major advantage of using heterogeneous catalysts is the ability to easily be separated from the products, thus eradicating the need for extensive separation methods such as separation through distillation or extraction.[6] However, the main disadvantage of using heterogeneous catalysts is the poor product selectivity.[8]

Homogeneous catalysts are made up of organometallic complexes which comprise of organic ligands coordinated to a metal centre.[9] They have significant advantages over heterogeneous catalysts (Table 1.1) because they display greater activity and selectivity at mild conditions.[16] These advantages are discredited by problems of separation of the product(s) from the catalyst, making the recycling and recovery of the often expensive and the declining transition metal resources a challenge.[17]

The difficulty to recover homogeneous catalysts arise because most separation techniques, like distillation, require elevated temperatures with the exception of catalytic reactions that yield volatile products.[15] Since most organometallic complexes are thermally sensitive and decompose at high temperatures, these separation techniques that involve high temperatures are unfavourable. Recent focus in the field of catalysis has been aimed at developing strategies that will provide a solution to this challenge. These strategies include supporting the catalysts on inorganic supports, polymers or dendrimers as well as immobilising the catalyst using biphasic media.[18,17] There has recently been a considerable interest in the synthesis of water-soluble metal complexes as catalyst precursors for a number of reactions such as hydrogenation,[19,20] carbonylation,[21] alkene metathesis[22,23] and hydroformylation.[17,24,25]

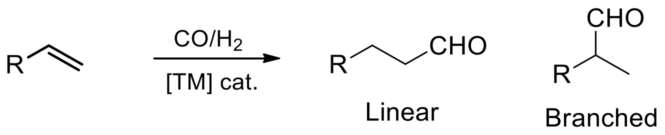
Table 1.1: Comparison of homogeneous and heterogeneous catalysts.[24]

	Homogeneous catalysts	Heterogeneous catalysts
Activity	High	Variable
Selectivity	High	Variable
Temperature and Pressure	Mild	Harsh
Service life of catalysts	Variable	Long
Sensitivity toward catalyst poisons	Low	High
Diffusion problems	None	May be important
Catalyst recovery	Difficult and expensive	Easy and cheap
Variability of steric and electronic properties of catalysts	Possible	Not possible

1.2 Hydroformylation

1.2.1 Discovery

The hydroformylation of longer chain alkenes (Scheme 1.1) is an important atom-economic process for producing aldehydes in order to make secondary products such as alcohols ethers and carboxylic acids.[26] The aldehydes produced can either be linear or branched and both forms are important in industry. Linear aldehydes are used to manufacture surfactants and plasticizers whereas branched aldehydes are important in pharmaceutical and agrochemical industries.[27] However, separating the catalyst and the product mixture is a challenge for homogeneous hydroformylation systems. Separation of the catalyst and the reaction products after a reaction can be achieved by expensive processes such as distillation.[28] Using the distillation process is energy intensive and often corrodes the equipment,[26] and leads to deactivation and decomposition of the catalyst.[25]

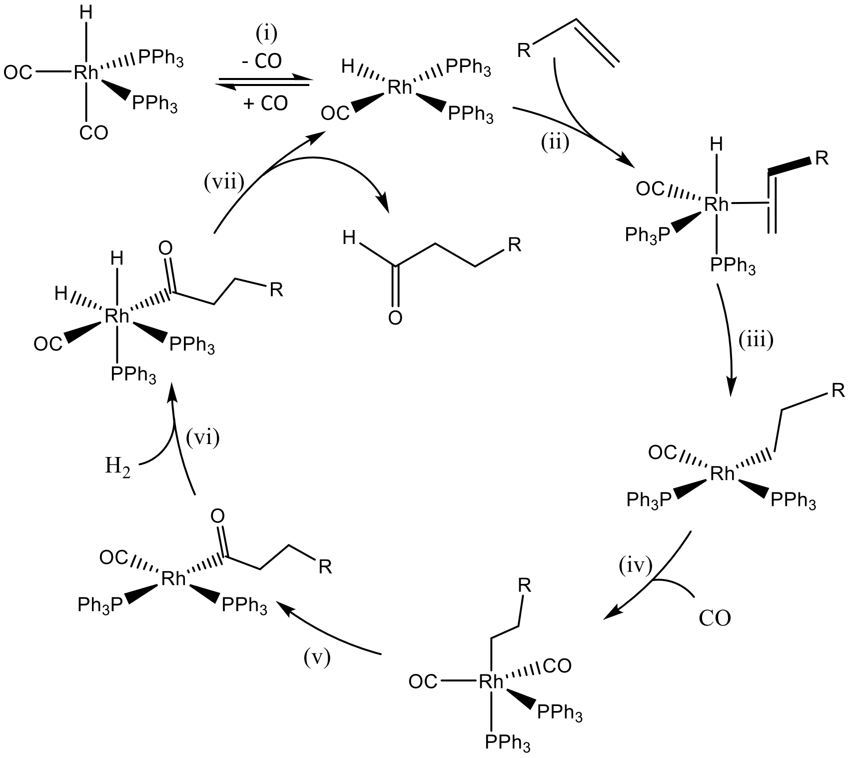


Scheme 1.1: Illustration of the hydroformylation reaction.

Hydroformylation (also known as the “oxo process”) was discovered by Otto Roelen in 1938 on his investigation of the oxygenated side products of cobalt-catalysed Fischer-Tropsch reactions. [26,29] The first hydroformylation process was catalysed using the cobalt precursor $[CoH(CO)_4]$ and was performed at a high temperature (150 - 180°C) and high pressure (200 – 350 bar).[30] The main disadvantage to using cobalt catalysts was that they have low chemoselectivity and regioselectivity[30] thus producing a large number of undesired products. This then encouraged the study of other metal complexes with the potential of being used for hydroformylation. Metals such as Rh, Pt, Ru, Ir, Os, Fe, Ni and Pd have been explored and their activity has been found to follow the trend: Rh>>Co>>Ir, Ru>Os>Pt>Pd>Fe>Ni.[31] The high catalytic activity of the rhodium-based catalysts, together with their better chemo- and regioselectivity led to rhodium-based catalysts replacing cobalt-based catalysts. Even though cobalt-based catalysts have been replaced by rhodium-based catalysts, a significant number of products (ca. 2.5 million tonnes per year) are still being produced using cobalt-based catalysts, specifically $[HCo(CO)_4]$ and $[HCo(CO)_3PPh_3]$.[29]

1.2.2 *Rhodium-catalysed hydroformylation*

The first rhodium-catalysed hydroformylation process was reported by Wilkinson in 1965 using the metal complex $[RhCl(PPh_3)_3]$.[32] Soon afterwards, in 1968, Wilkinson and colleagues reported a hydroformylation process using the catalyst precursor $[RhH(CO)_2(PPh_3)_2]$, the catalytic cycle using this catalyst is shown in Scheme 1.2. The descriptions of each step in the cycle are outlined in Table 1.2. This reaction occurs under mild conditions and has good chemo- and regioselectivity.[33] Rhodium-catalysed systems then received much attention and extensive study went into synthesizing the rhodium-based catalysts for use in hydroformylation. Great progress on the improvement of rhodium-based catalysts for better chemo- and regioselectivity have been achieved to date and more studies are still being conducted.[34–36]



Scheme 1.2: Catalytic cycle of the rhodium-catalysed hydroformylation reaction yielding the linear aldehyde.[33,37]

Table 1.2: Descriptions of the steps in the Rh-catalysed hydroformylation cycle.[37]

Step	Description
i	Dissociation of CO resulting in the 16-electron rhodium complex.
ii	Olefin coordination to a vacant site forming a 5-coordinate intermediate.
iii	Migratory insertion of the olefin resulting in a 4-coordinate complex.
iv	Association of CO.
v	Migratory insertion of CO into the alkyl ligand giving a Rh-acyl complex.
vi	Oxidative addition of H_2.
vii	Reductive elimination of the aldehyde (could either be linear or branched).

Rhodium-containing hydroformylation catalysts are more stable under mild reaction conditions than other transition metal-catalysed hydroformylation reactions. Rhodium-based metal complexes have high catalytic activity, reaction rates and better selectivity for aldehydes.[38] There are however difficulties to separate the Rh-based catalysts from the long chain aldehyde products. The difficulty in catalyst recovery, coupled with the greater expense of the rhodium metal, requires strategies to warrant element sustainability.[18]

Different strategies have been developed to overcome this challenge, one of the strategies employed is the process of biphasic systems in which the catalyst is immobilised in a different phase from the substrate and products.[27]

1.3 Biphasic catalysis

The biphasic catalysis technique has been greatly implemented in hydroformylation reactions because it introduces a balance between both homogeneous and heterogeneous catalysis.[39] In a biphasic process, the catalyst is in a different phase from the reactants.[24] The catalyst is thus heterogeneous with respect to the reactants. At room temperature, the two phases are immiscible, the two phases only come into contact and become a homogeneous mixture when high temperatures, pressure and vigorous stirring are applied, and the catalytic reaction takes place. This brings the advantages of heterogeneous catalysis in a homogeneous system.[39] When the reaction is complete, the catalyst remains in one phase, different from the product phase. The biphasic system permits the catalyst to be separated from the products by simple decantation and to be reused with minimal loss of catalytic activity and selectivity. Figure 1.3 illustrates the principle behind the biphasic catalysis process. The ability to recycle the catalyst from this process is both economically beneficial and advantageous to the environment.[39,40] There is increased interest in the study and synthesis of water-soluble Rh(I) metal complexes for use as catalysts in biphasic hydroformylation.[13]

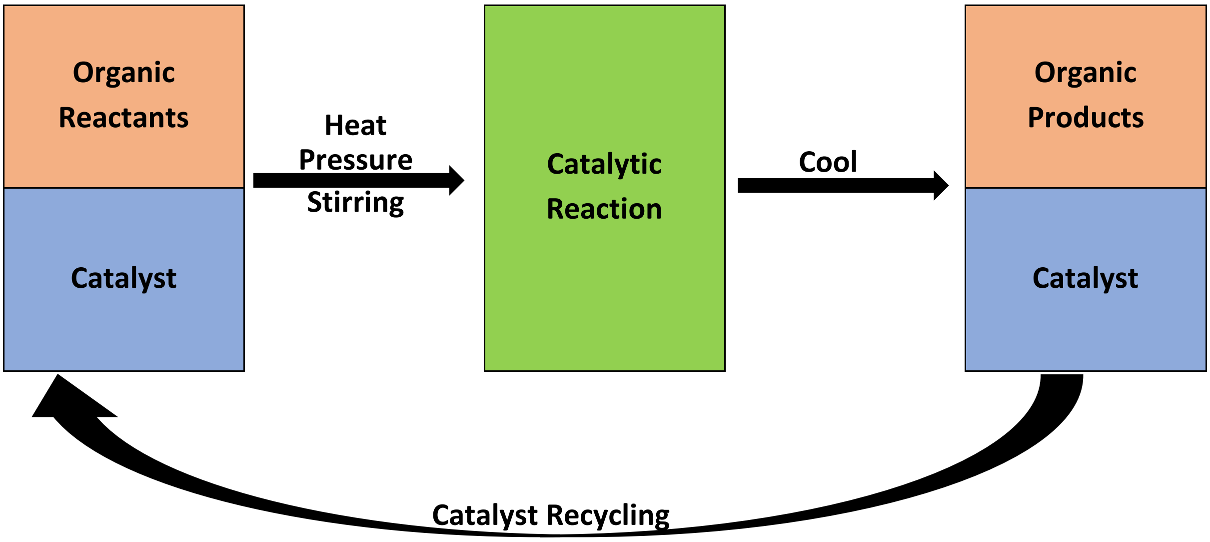


Figure 1.3: Illustration of biphasic catalysis

Various solvents which are immiscible with organic solvents can be utilized to create the biphasic media such as fluorous, ionic liquids, supercritical carbon dioxide and aqueous biphasic systems.[26,27,41]

1.3.1 Fluorous solvents

Fluorous biphasic systems are made up of two phases, an organic phase that has the organic substrates dissolved in an organic solvent and a fluorous phase that has the fluorocarbon-containing catalyst in a fluorinated solvent.[27] Fluorinated solvents are immiscible with water and the majority of the organic solvents, thus the separation of the catalyst from the product after the catalytic reaction is simplified.[42] The first introduction of fluorous biphasic catalysis was in 1994 in a seminal paper by Horváth and Rábai.[42,43] They realized that the ligand had to be appropriately derivatised with long perfluoroalkyl substituents since only highly fluorinated compounds are soluble in the highly unreactive perfluorinated solvents. To be able to dissolve a metal complex in a perfluorinated solvent, the addition of long perfluoroalkyl side-chains is required, these side-chains are referred to as fluorous ponytails. Ligands that have a vast amount of these ponytails, such as the ones shown in Figure 1.4, are prepared in order to prepare metal complexes that are soluble in perfluorinated solvents. Studies have shown that a composition of approximately 66 % fluorine (with respect to weight) is required to achieve perfluorocarbon solubilty.[43,44]

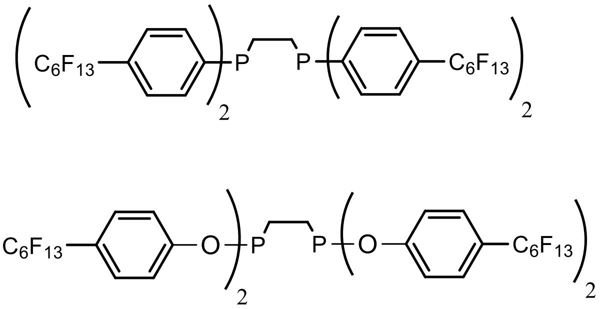


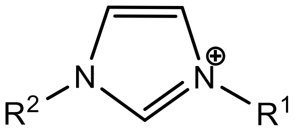
Figure 1.4: Examples of perfluoroalkyl-substituted phosphorus ligands.[43]

Stevens and co-workers[45] studied the biphasic hydroformylation of 1-decene in a toluene/$C_6F_{11}CF_3$ solvent mixture using the fluorous-soluble hydroformylation catalyst, $[HRh(CO)\{P(CH_2CH_2(CF_2)_5CF_3)_3\}_3]$. Conversions of up to 98 % were obtained and 90 % of the products were aldehydes. The catalyst exhibited high regioselectivity, with the *n*:*iso* ratio reaching as high as 8. The catalyst was recycled nine times with the overall turnover number of more than 35 000 mol of aldehyde produced per mole of catalyst used, a constant loss of only 4.2 % of rhodium into the toluene layer was measured after each run.[45]

1.3.2 Ionic liquids

Ionic liquids (ILs) are classified as salts that are liquids at (or close to) ambient temperature. ILs are considered to be green solvents; they are colourless, non-flammable and have a negligible vapour pressure.[46–48] ILs have properties that render them appropriate to be utilized in homogeneous catalysis. They have the ability to solubilise gases such as H_2, CO and O_2 and hence ILs have been utilised for hydrogenation,[49,50] carbonylation,[51,52] hydroformylation[28,53] and aerobic oxidation reactions.[54–56] Ionic liquids are generally immiscible with some organic solvents and can thus be utilized for biphasic catalysis. Furthermore, ILs have the potential to be reused and recycled.[46,48] Lipophilic ILs can also be used for aqueous biphasic catalysis. In addition, ILs can be used for triphasic catalysis in which the catalyst is in the ionic liquid phase, the substrate and the product in the organic phase and the aqueous phase contains the salts formed during the catalytic reaction. ILs are considered ‘designer solvents’ because their lipophilicity, hydrophilicity and polarity can be modified by selection of a suitable anion/cation.[46] Figure 1.5 shows an example of a popular ionic liquid cation, 1,3-dialkylimidazolium, and several anions.

Cation:



Anions: BF_4^-, PF_6^-, NO_3^-, Cl^-, $CH_3CO_2^-$

Figure 1.5: The 1,3-dialkylimidazolium cation and several anions.

The use of functionalised ionic liquids (FILs) is also common in biphasic systems. FILs such as phosphine-FILs have been extensively studied as an efficient solvent for immobilizing metal catalysts. The advantage is that the strong coordination of the metal centre to the phosphine-FILs tightly captures the metal catalyst, increasing the catalyst's solubility in the IL.[53]

Wasserscheid and co-workers[57] investigated the rhodium-catalysed hydroformylation of 1-octene in a 1-butyl-3-methylimidazolium hexafluorophosphate (bmimPF$_6$)/toluene biphasic system. The catalyst was generated *in-situ* from the [Rh(CO)$_2$(acac)] precursor and the guanidine-modified diphosphine ligand containing a xanthene backbone (Figure 1.6). High regioselectivities were obtained, with *n*:*iso* ratios as high as 20. The catalyst was also recycled ten times with an overall turnover number of 3 500 mol of product formed per mol catalyst used. The leaching of rhodium into the organic layer was found to be very low (less than 0.07 %).[57]

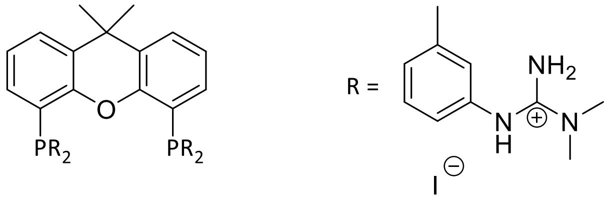


Figure 1.6: The guanidine-modified diphosphine ligand used by Wasserscheid.[57]

There are a few disadvantages associated with using ILs for biphasic catalysis. ILs are non-volatile thus purification cannot be achieved by distillation. This then implies that they need to be initially synthesised with high purity. A large quantity of ionic liquid is needed for utilization in biphasic catalysis, this is an economical and toxicological challenge.[28] When ILs are used on an industrial scale, small quantities of ILs will unavoidably find their way into the environment through mechanical loss and their potential environmental impact is not fully known.[46]

1.3.3 Supercritical carbon dioxide

Supercritical carbon dioxide (scCO$_2$) is an eco-friendly and economically practical solvent for biphasic metal catalysed reactions. ScCO$_2$ is non-flammable, non-toxic and there is no presence of a gas-liquid phase boundary when used in biphasic systems. This then renders scCO$_2$ a practical alternative over regular organic solvents.[58,59] Modifying the pressure and temperature can tune the physicochemical properties of $scCO_2$ up to a certain point. The main disadvantage to using $scCO_2$ as a solvent for biphasic catalysis is the fact that phosphine ligands have poor solubility in $scCO_2$, and considering that most catalysts used for hydroformylation are phosphine based, most catalyst systems perform poorly when $scCO_2$ is used. To overcome this shortcoming, scientists are working at improving the solubility of phosphine ligands in $scCO_2$ by using fluorous substituents.[59]

A different approach can be to use $scCO_2$ in conjunction with ILs, where the catalyst is retained in the IL and the product in the $scCO_2$ and thus the catalyst can be recycled.[60] Webb and co-workers reported on the hydroformylation of 1-octene using a $Rh/(Ph_2PC_6H_4SO_3)(bmim)$ catalyst in a $bmimPF_6/scCO_2$ biphasic system. They obtained high conversion of the substrate (80 %) and managed to re-use the catalyst nine times with minimal catalyst leaching (< 0.03 %).[61]

1.3.4 Water

Water has been the solvent of choice in the application of two-phase catalysis for hydroformylation.[62] It is the ideal solvent because it is eco-friendly, user-friendly, non-toxic, abundant (hence relatively cheap) and non-flammable. Such properties are in line with green chemistry principles (Table 1.3). Moreover, water is immiscible with most organic solvents, therefore making it easier to recover the water-soluble catalysts that are retained in the aqueous layer after completion of the catalytic reaction.[18]

Table 1.3: The 12 Principles of Green chemistry.[63,64]

Green Chemistry Principles
1. Prevention: It is better to prevent waste than to treat or clean up waste after it is formed.
2. Atom Economy: Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Less hazardous chemical synthesis: Whenever practicable, synthetic methodologies should be designed to use and generate substances that pose little or no toxicity to human health and the environment.
4. Design safer chemicals: Chemical products should be designed to preserve efficacy of the function while reducing toxicity.
5. Safer solvents and auxiliaries: The use of auxiliary substances (e.g. solvents, separation agents, etc) should be made unnecessary whenever possible and, when used, innocuous.
6. Design for energy efficiency: energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. Use of renewable feedstocks: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. Reduce Derivatives: Unnecessary derivatisation (use of blocking groups, protection/deprotection, and temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. Catalysis: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Design for degradation: Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. Real time Analysis for pollution prevention: Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. Inherently safer chemistry for accident prevention: Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including release, explosions and fires.

Water as a solvent has exceptional properties. It has an extremely small molecular volume, its hydrogen bonds form a tetrahedral molecular network and it has isothermal compressibility. These properties render it perfect for reactions where hydrophobic and hydrophilic effects have to be taken into account. Water thus has a remarkable effect in chemical reactions.[62] Aqueous biphasic systems combine both the positive properties and characteristics of water and the favoured advantages of homogeneous catalysis.[65]

1.4 Aqueous biphasic systems for hydroformylation

Aqueous biphasic homogeneous catalysis was initially reported by Manassen in 1973. This was then followed by research work by E. G. Kuntz in 1975-1979 and was only used industrially in 1984 at Rührchemie AG for the hydroformylation of propylene, known as the Ruhrchemie/Rhône-Poulenc (RCH/RP) process and only then was there a scientific study.[24,29,62,66] The RCH/RP process is the most extensively studied of the biphasic systems and is one of the first industrially commercialised aqueous biphasic processes to make use of the hydroformylation reaction. This process uses water-soluble catalysts for the hydroformylation of propylene to butyraldehyde (or 1-butene to valeraldehyde). RCH/RP uses a highly water-soluble Rh(I)/TPPTS catalyst (TPPTS = 3,3′,3″-Phosphanetriyltris(benzenesulfonic acid) trisodium salt). Figure 1.7 shows the structure of the metal complex and Figure 1.8 illustrates the basic flow-scheme of the process. Initially, the RCH/RP process suffered a lot of scepticism, ruling out the concept of water-soluble organometallic complexes as catalysts, but now it has grown to be the major producer of aldehydes, producing over 12 million tonnes per annum. [17,24,62,67]

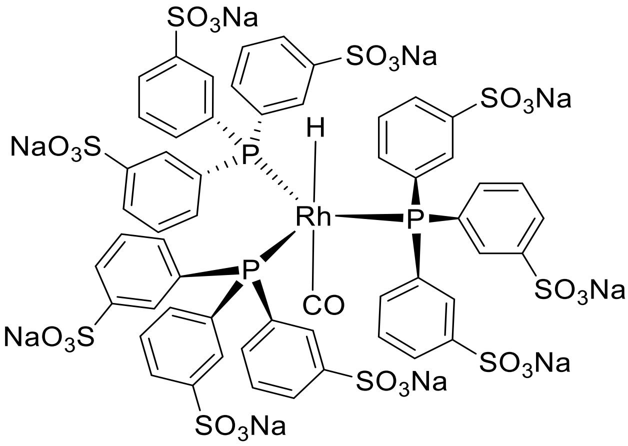


Figure 1.7: The Rh/TPPTS metal complex.

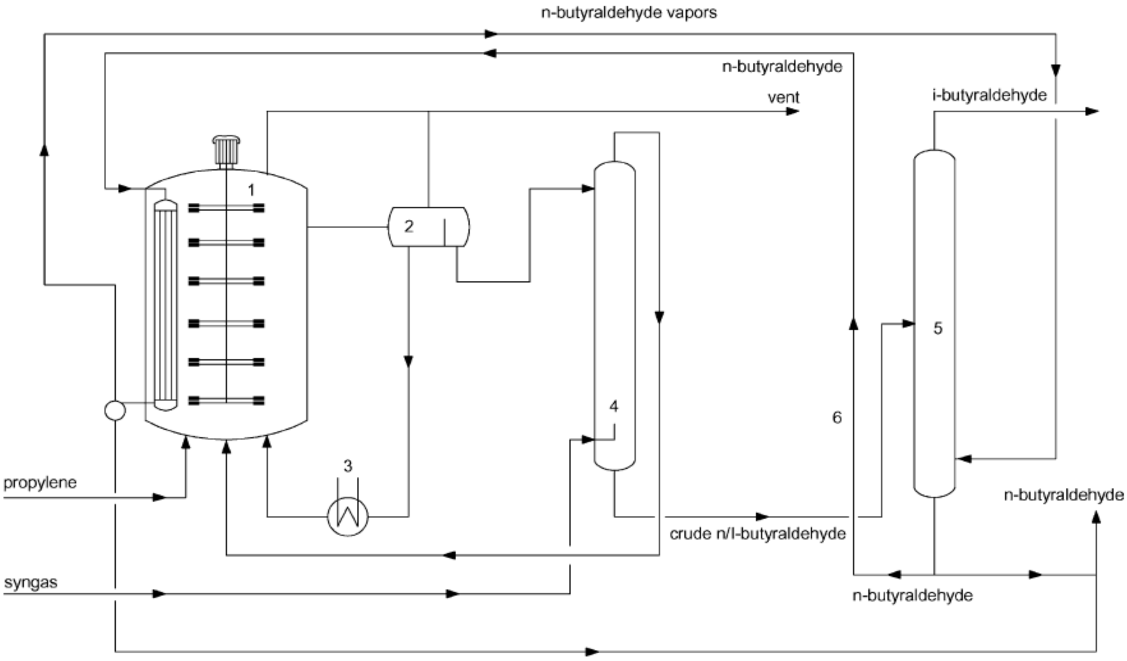


Figure 1.8: Basic flow-scheme of the RCH/RP process; (1) Reactor, (2) Decanter, (3) Heat Exchanger, (4) Stripping column, (5) Distillation, (6) Recycle of the coolant *n*-butyraldehyde.[65,66]

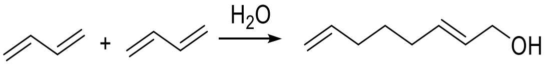
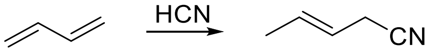
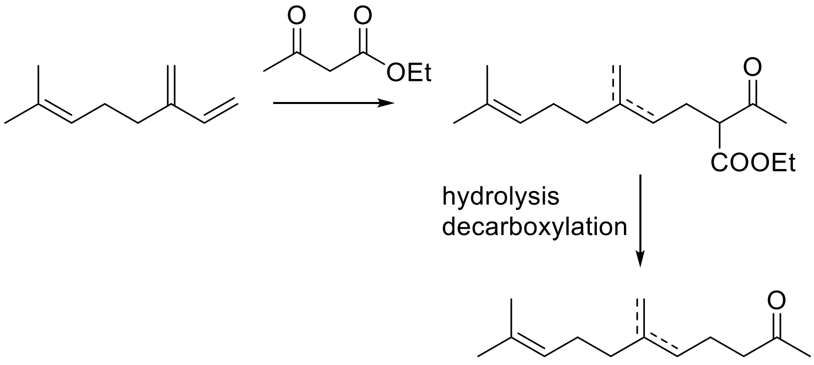
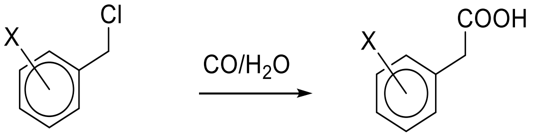
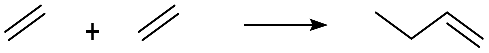
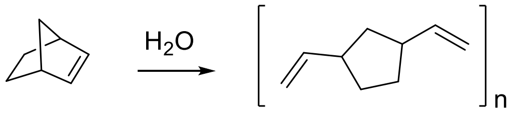
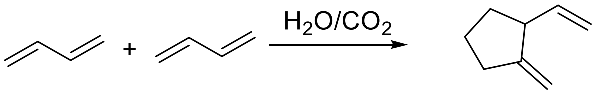
As the OXEA process (the RCH/RP process) was at its infancy, a lot of things were different from the hydroformylation process that had been in use until then: i) The catalyst – For the first time the catalyst was applied in aqueous form, ii) The process procedure, iii) The reactor – The special mixing of the two phases, iv) The process becomes a net steam supplier due to the energy balance and v) recyclability – the simple recycling of the catalyst.[65] The RCH/RP process is highly efficient, the catalyst is said to display high activity and selectivity (up to 98%) for the linear aldehyde. Furthermore, this process has low catalyst leaching and high catalyst recyclability, making it economically and environmentally advantageous. Table 1.4 gives the conditions at which this process occurs and the results thereof.[29,65]

Table 1.4: Conditions and results of the RCH/RP process.[62,65]

	Typical value	Variance
Selectivities		
Towards C_4 Products (%)	>99.5	>99
Towards C_4 Aldehydes (%)	99	99
Products		
n-butyraldehyde (%)	94.5	92-97
iso-butyraldehyde (%)	4.5	3-8
n-butyralcohol (%)	0.5	0.5
iso-butyralcohol (%)	<0.1	<0.1
Butyl formats (%)	Traces	Traces
Reaction conditions		
Temperature (°C)	120	110 – 130
Total pressure (Mpa)	50	30 – 60
Heat recovery (%)	>99	>99
CO/H_2 ratio	1.01	0.98 – 1.03
Aqueous/Organic phase ratio	6	4-9
Propylene quality (% propene)	95	85 – 99.9

Apart from hydroformylation, aqueous biphasic catalysis is used in other bulk processes such as the hydrodimerization of butadiene and water, hydrocyanation, cyclodimerization, the production of geranyl acetone (a precursor of vitamin E), the production of phenyl acetic acid, hydrogenation and many other processes.[24,68–70] Table 1.5 states the different processes that aqueous biphasic catalysts can be used in, their reaction schemes and the possible catalysts used.

Table 1.5: Some of the processes that utilize aqueous biphasic catalysis.[24,68–70]

Process	Reaction scheme	Typical metal/ligand
Hydrodimerization		Pd/TPPMS
Hydrocyanation		Ni
Production of geranyl acetone		Rh/TPPTS
Production of phenyl acetic acid		Pd/TPPTS
Oligomerization		Ni
Metathesis		Ru/TPPTS
Cyclodimerization		Pd

1.4.1 Typical ligands used for aqueous biphasic catalysis

There is one considerable stumbling block associated with aqueous biphasic catalysis. Even though the hydroformylation process uses olefins with the number of carbon atoms of up to 16, the aqueous biphasic system has only been limited to propylene (3 carbon atoms) and butylenes (4 carbon atoms).[39,66] This is due to the fact that higher olefins have poor solubility in water and for an efficient hydroformylation process, the substrate must dissolve sufficiently in the aqueous phase for the chemical reaction to take place. The most common strategy employed in resolving this challenge is to keep the long chain olefins dissolved in the organic layer and design catalysts which have both hydrophobic and hydrophilic properties. This increases the affinity of the catalyst to the organic solvent as the catalytic reaction takes place, but also allows for the retention of the catalyst in the aqueous layer due to its water-soluble properties. To achieve this, amphiphilic ligands are introduced to the coordination sphere of the metal centre. Sulfonated phosphine ligands with long aliphatic pendant arms (an example shown in figure 1.9) have been previously used for this purpose.[29,39,71,72]

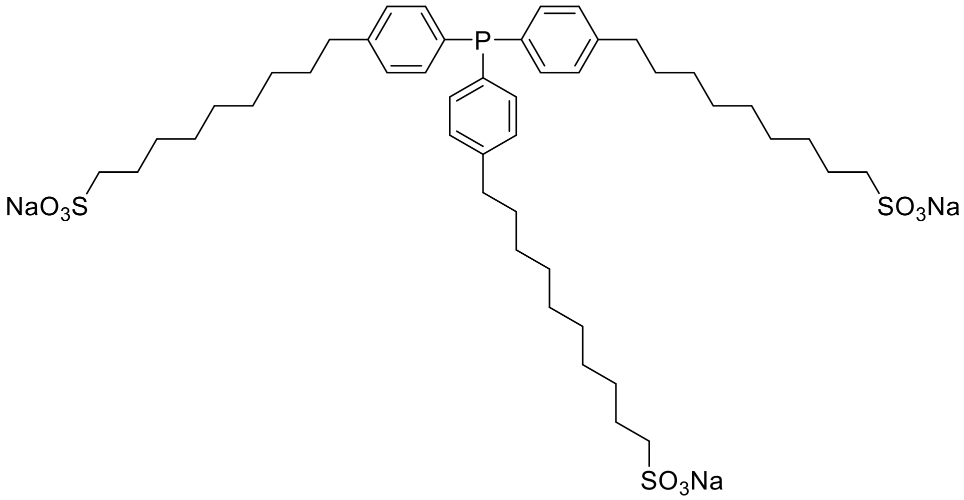


Figure 1.9: An example of a sulfonated phosphine with long aliphatic pendant arms.[71]

Ligands are a very important aspect of a catalyst as different ligands possess different steric and electronic properties that affect the catalyst's activity and selectivity; hence ligand modification is of great interest. A lot of work has gone into the development and improvement of catalytic rates and selectivity by ligand design. These include monodentate and bidentate phosphorus-based ligands,[73] N-heterocyclic carbene[74,75] and P,O- and P,N-ligands[76,77] have been studied and their electronic and steric properties tuned.[53] Changing electronic and steric factors influences the catalytic centre which then affects the hydroformylation rates and substrate conversion.[17] The use of phosphine ligands is advantageous because they can be modified easily by using a variety of organic substituents which then affords the fine tuning of electronic and steric characteristics of the catalyst. In homogeneous catalysis, electronic and steric properties are important in the activity and selectivity of the catalyst. Substituents such as hydroxyl or amino functionalities and ionic groups such as sulfonate, carboxylate and ammonium can be added to the phosphine ligand to maximise its water-solubility.[16,78,79]

To achieve water-soluble metal complexes, hydrophilic ligands are usually introduced into the coordination sphere of the metal centre.[13] TPPTS and many other tertiary water-soluble phosphines are the most used group of water-soluble ligands. This is because they have neutral donating ability which in turn stabilizes the metal centre during the catalytic cycles.[80] A lot of other water-soluble ligands have been studied but only TPPTS has been shown to be economical when considering price to performance ratio.[65] Apart from TPPTS, various other sulfonated phosphines have been studied. These include bis(diphenylphosphine)biphenyl (BISBIS), with varying degrees of sulfonation, and the sulfonated 2,2'-bis(diphenylphosphinomethyl)-1,1'-binaphthyl (NAPHOS) referred to as BINAS.[62,81] Even though BINAS showed greater selectivity and was more active than the others,[82,83] TPPTS is still the best ligand of choice because BINAS has shown higher decomposition rates than TPPTS.[65] In addition, the TPPTS ligand effectively carries all of the rhodium metal used in the aqueous phase.[65] There is on-going research to develop other water-soluble ligands in order to overcome challenges associated with the poor water-solubility of metal complexes.

1.4.2 1,3,5-Triaza-7-phosphaadamantane (PTA) as a ligand

Transition metals can be made to achieve water-solubility by introducing phosphine ligands that possess polar functionalities such as sulfonates, carboxylates and hydroxyls. One phosphine ligand that possesses amine functionality is 1,3,5-triaza-7-phopsphaadamantane (PTA), shown in figure 1.10. PTA-ligated metal complexes have been studied extensively and have been proven to be useful in catalysing many chemical reactions.[12,84–86] PTA is a neutral cage-like ligand and was first synthesised in 1974[87] and has been vastly used in the preparation of a number of water-soluble transition metal complexes for utilization in aqueous biphasic catalysis and as luminescent materials.[78,88] The need to develop sustainable catalytic processes and the discovery that PTA-metal complexes have an exceptional binding activity for both DNA and proteins that show cytotoxicity towards specific tumour cells sparked a renewed interest in PTA.[13]

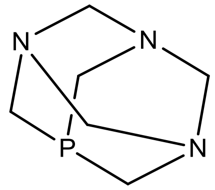


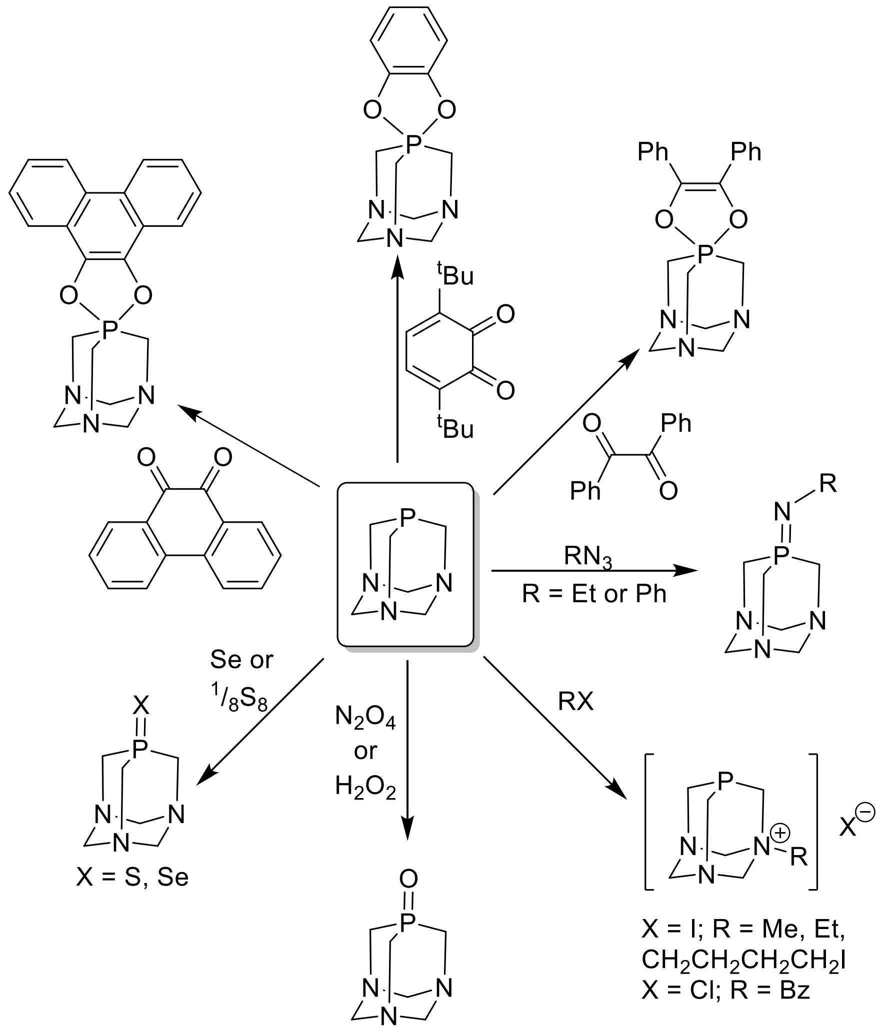
Figure 1.10: Structure of 1,3,5-triaza-7-phosphaadamantane (PTA).

PTA, a water-soluble phosphine, owes its water-solubility to its nitrogen atoms forming hydrogen bonds with water. PTA has a small cone angle (103°) and a strong donating ability. Extensive study has been dedicated to it as a potential ligand for catalytic reactions. A lot of PTA derivatives have been synthesised but most of them have not been studied further.[25,80,88] In comparison with other alkyl and aryl-phosphines the cone angle of PTA is relatively small (Table 1.6). This gives PTA an undemanding steric characteristic and, together with the thermal and chemical stability and its favourable hydrophilicity, makes this ligand unique as compared to the less restricted phosphines such as trimethylphosphine (PMe_3).[78]

Table 1.6: Cone angles for different phosphine ligands.[78]

Phosphine	Cone angle (°)
PH_3	91
PH_2Me	103
PTA	103
PEt_3	110
$PPhH_2$	127
PMe_3	134
$P(i\text{-}Pr)_3$	135
PPh_3	145
PCy_3	170
$P(t\text{-}Bu)_3$	182
$P(Mes)_3$	212

PTA derivatives have been synthesised and studied in an attempt to increase the water-solubility of the ligand (and hence the water-solubility of the corresponding metal complexes). PTA can be derivatised by reactions with acetic anhydride, MeI (or $MeOSO_2CF_3$), EtI, $I(CH_2)_4I$ and $PhCH_2Cl$ to produce the water-soluble di-*N*-acylated compound 3,7-diacetyl-1,3,7-triaza-5-phosphabicyclo[3.3.1]nonane (DAPTA), and the *N*-alkylated compounds [PTA(R)]X (R = Me, Et, $(CH_2)_4I$ and $PhCH_2$) respectively. The resulting *N*-alkylated PTA salts bind to the metal centre via the phosphorus atom.[78,88] Scheme 1.3 shows some PTA derivatisation reactions. A vast number of PTA-metal complexes have been explored since PTA was initially synthesised[12,78,84,85] but a great deal of attention has been given to rhodium-PTA systems in light of their potential catalytic activity.[78,86,89,90]



Scheme 1.3: PTA derivatisation reactions.[78,88]

Just as the recoverability of the catalysts is important, the reaction rate, catalyst activity and selectivity are also important factors. A more recent approach to improving these factors of a catalyst precursor has been to increase the number of metal centres in a complex. This introduces co-operative interactions that may exist between proximate metal centres, enhancing catalytic activity compared to the mononuclear analogues.[91]

1.5 Polymetallic (bi- and trimetallic) complexes

Researchers, motivated by nature itself, are developing polymetallic catalytic systems. Nature has the most selective catalysts that contain two or more metal centres, referred to as metalloenzymes.[17,92–94]. The combination of multiple active centres induces very unique properties (both chemical and catalytic) and often leads to faster reaction rates, high catalytic activity and improved selectivities.[17,92,95,96] One metal can act as the main catalytic centre while the other metal acts as an electronic reservoir, which then stabilizes the electron density around the catalytic centre.[97] Cooperativity between two metal centres may also exist; thus if two metals are an appropriate distance from each other, higher reactivity and selectivity can be achieved as compared to when using the monometallic complexes. Figure 1.11 shows the different kinds of bimetallic complexes.[98]

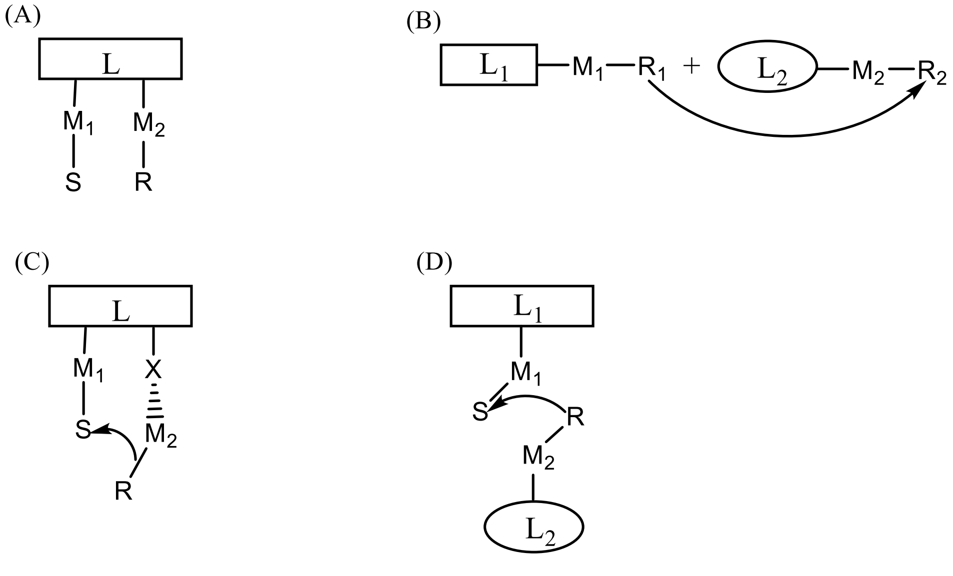
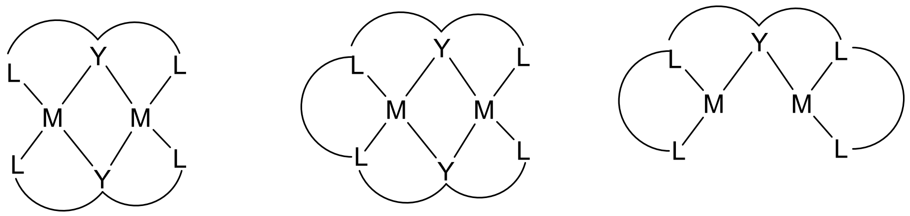


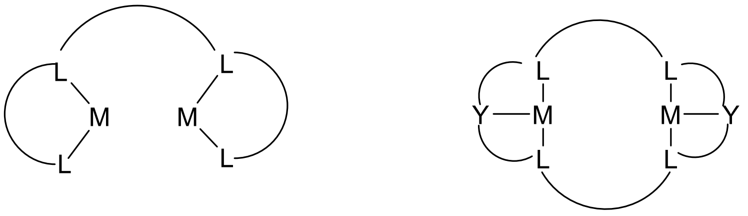
Figure 1.11: Illustration of the different kinds of bimetallic catalysts. M: Metal, L:ligand, S: substrate and R:reactant.[94]

Bimetallic complexes usually exhibit distinct electronic and chemical properties which are different from those of the parent metals. These properties make it possible to have catalysts with better chemical stability, catalytic activity and selectivity.[99] The electronic and chemical properties are affected by two factors: i) the heteroatom bonds that are formed modify the metal centre's electronic environment, thus leading to changes in its electronic structure by the ligand effect, ii) the geometry of the polymetallic complex becomes distinct from that of the parent metal.[100] This then implies that polymetallic complexes catalyse reactions more efficiently or in a manner that is not the same as if two isolated metal centres were used.[94]

The choice of ligand is very important when synthesising polymetallic complexes. The ligand system needs to be able to accommodate more than one metal centre.[101] Moreover, the ligands characteristics (Flexibility, steric properties, electronic properties and bridging ligand features) are very important as they determine the nature of the metal centre i.e. the type of metal that can be bound, the metal's oxidation state and whether or not one can have a homo- or heterobimetallic complex.[101] The ligands can be isolated into two classes shown in figure 1.12; a) Ligands which result in complexes in which the metal centres share at least one donor atom. These ligands contain at least one donor atom that provides a bridge between metals. b) Ligands with multiple donor atoms that are not shared.[94]



Class (a) examples of dinuclear complexes of compartimental ligands.



Class (b) examples of dinuclear complexes of ligands with isolated donor sets

Figure 1.12: Illustrations of the different ligand classes and how they coordinate to the metals. M: metal; L,Y: donor atoms.[94]

There are a number of examples of dinuclear rhodium complexes that have been used successfully in hydroformylation reactions.[94,102,103] Stanley and co-workers synthesised and used the bimetallic complex *rac*-$[Rh_2(nbd)_2(et,ph\text{-}P4)]^{2+}(BF_4^-)_2$ (nbd = norbonadiene, et = ethyl, ph = phenyl) as a pre-catalyst for the hydroformylation of 1-hexene. The complex exhibits increased activity and selectivity, the hydroformylation of 1-hexene is about 40 % faster when catalysed by the Rh_2 complex synthesised by Stanley than when employing the commercial Rh/PPh_3 catalyst. Linear:branched product selectivity is also 9 times greater than when using the monometallic analogue (Figure 1.13).[103]

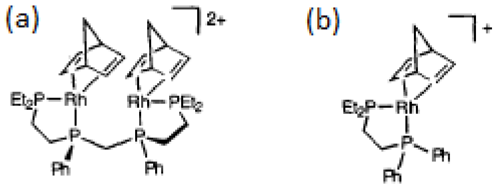
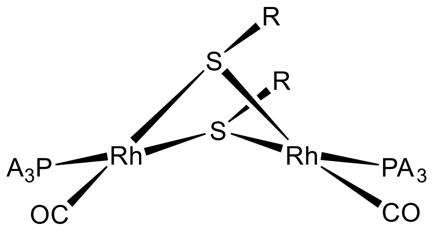


Figure 1.13: The (a)Bimetallic and (b)Monometallic complexes synthesised by Stanley and Co-workers.[103]

Kalck and co-workers also studied the hydroformylation of 1-hexene using a series of rhodium bimetallic complexes, $Rh_2(\mu\text{-}SR)_2(CO)_2(PA_3)_2$ (where R = ^tBu, C_6F_5 and A = Ph, OPh, OMe), as catalyst precursors. They found that the complexes catalyse the hydroformylation of 1-hexene at relatively low pressure (5 bar) in comparison to most rhodium catalysts. The complexes exhibited higher conversion rates when compared to Wilkinson's catalyst $HRh(CO)(PPh_3)_3$ and largely avoided isomerisation of the alkene. No hydrogenation products (alkanes and alcohols) were observed, each complex was highly selective for aldehydes, in particular, linear aldehydes. The catalyst precursors were also recovered unchanged after the catalytic reaction and could thus be reused.[104,105]



R = ^tBu, C_6F_5
A = Ph, OPh, OMe

Figure 1.14: The Bimetallic complexes used in the hydroformylation of 1-hexene by Kalck and Co-workers.[104,105]

1.6 Motivation of this study

The need for catalyst recyclability has sparked a great interest in the synthesis of water-soluble catalysts to be used in the aqueous biphasic hydroformylation of olefins. This is due to challenges of separating the relatively expensive Rhodium-based catalysts from the products after completion of the homogeneous hydroformylation reaction. To increase a catalyst's water-solubility, water-soluble ligands have to be coordinated to the metal centre, this then improves the retention of the catalyst in the aqueous layer and it can easily be recycled. There is minimal documentation on the biphasic hydroformylation of olefins using water-soluble PTA-based rhodium complexes, prompting interest in the investigation of such systems. Furthermore, research on improving catalyst activity and selectivity is still on going. The most recent approach has been to increase the number of metal centres in a catalyst, motivated by the great activity and selectivity exhibited by metalloenzymes. This prompted interest in synthesising polymetallic water-soluble complexes and evaluating their activity, selectivity and recyclability when used as pre-catalysts in the aqueous biphasic hydroformylation of 1-octene.

1.7 Concluding remarks

The hydroformylation reaction is an extensively studied process and much attention has been given to the design and synthesis of new metal complexes that exhibit faster rates, improved catalytic activity, greater product selectivity and better recyclability. Rhodium-based metal complexes are generally the complexes of choice for use as catalyst precursors in hydroformylation reactions due to their high catalytic activity and selectivity under mild conditions (low temperature and pressure) and their better stability compared to other metal complexes.

A lot of work has gone into investigating the recyclability of catalysts. Coordinating water-soluble ligands, such as 1,3,5-triaza-7-phosphaadamantane (PTA), to the metal centre gives rise to water-soluble complexes which can be employed in the aqueous biphasic hydroformylation of olefins and thus improve on catalyst recyclability. The use of phosphine ligands is advantageous because they can be modified easily by using a variety of organic substituents which then affords the fine tuning of electronic and steric characteristics of the catalyst. The catalyst's activity and selectivity may also be improved by increasing the number of metal centres.

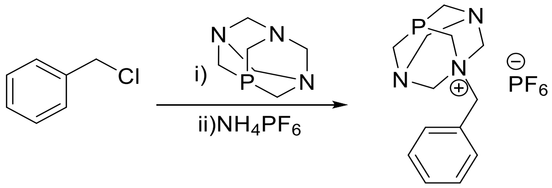
1.8 Aims and Objectives

1.8.1 Aims

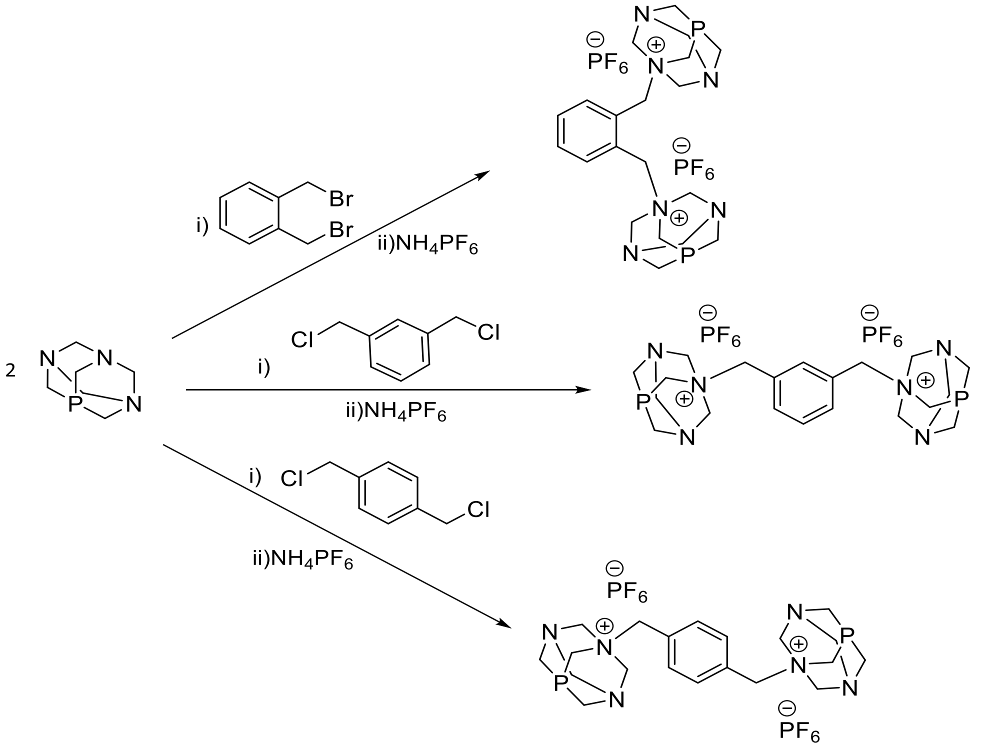
The main aim of this project is to design, synthesise and characterise mono and polynuclear PTA-based rhodium(I) water-soluble organometallic complexes and evaluate their catalytic activity, product selectivity and recyclability when used in biphasic hydroformylation of olefins.

1.8.2 Specific objectives

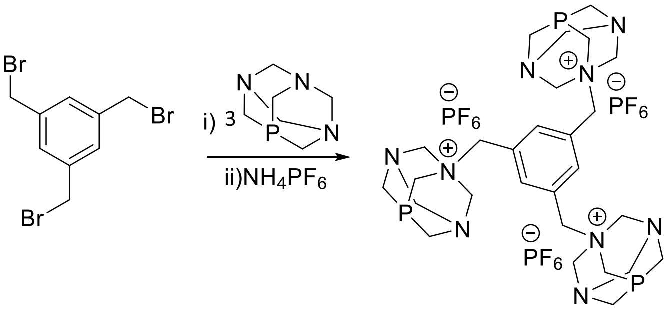
- To synthesise and characterise the water-soluble PTA ligands.[88,90,106,107]



Scheme 1.4: Synthesis of the monomeric ligand.[90]

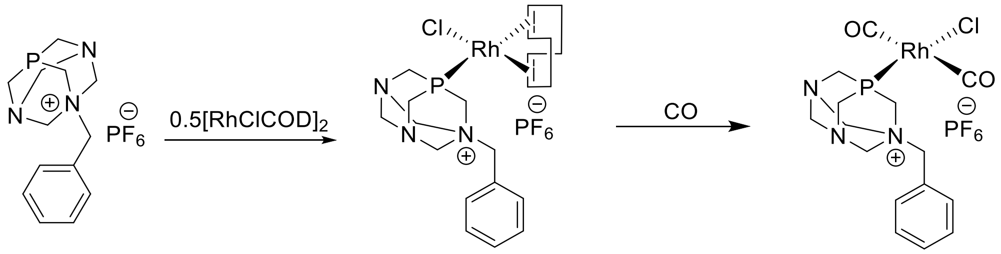


Scheme 1.5: Synthesis of the dimeric ligands.[88,106]

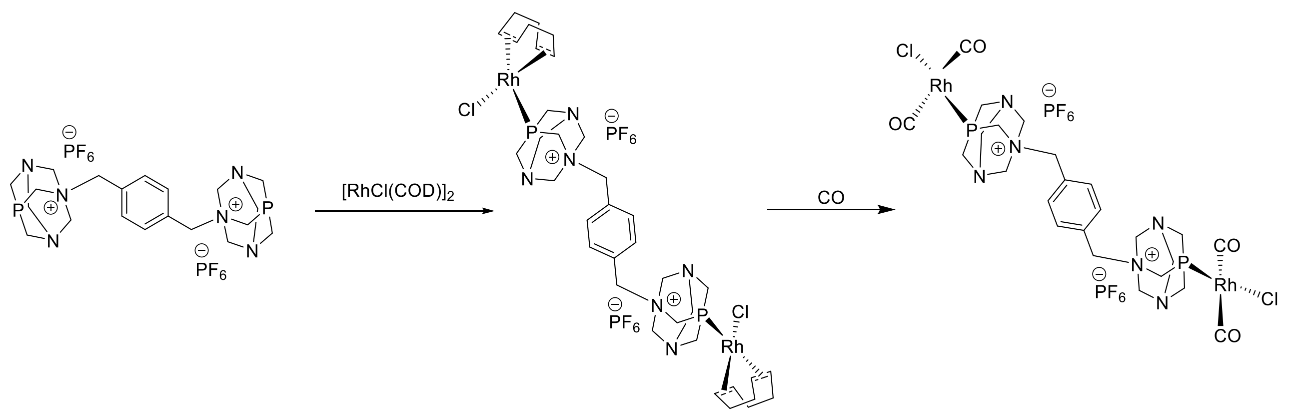


Scheme 1.6: Synthesis of the trimeric ligand.[107]

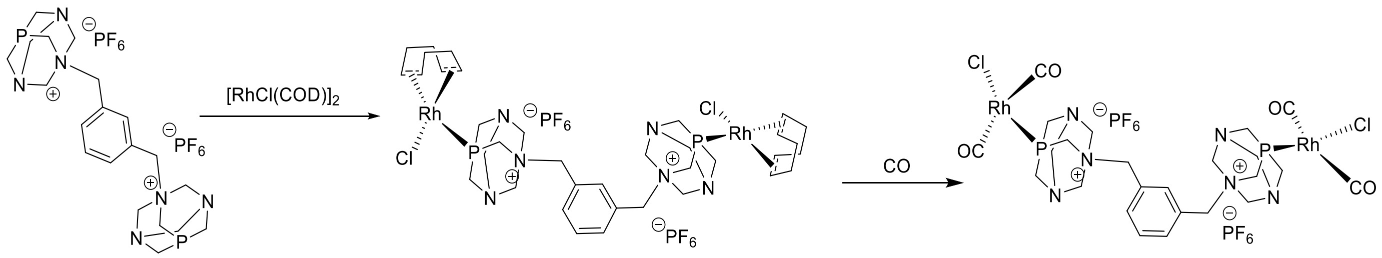
- To synthesise and characterise the water-soluble PTA-based rhodium complexes.



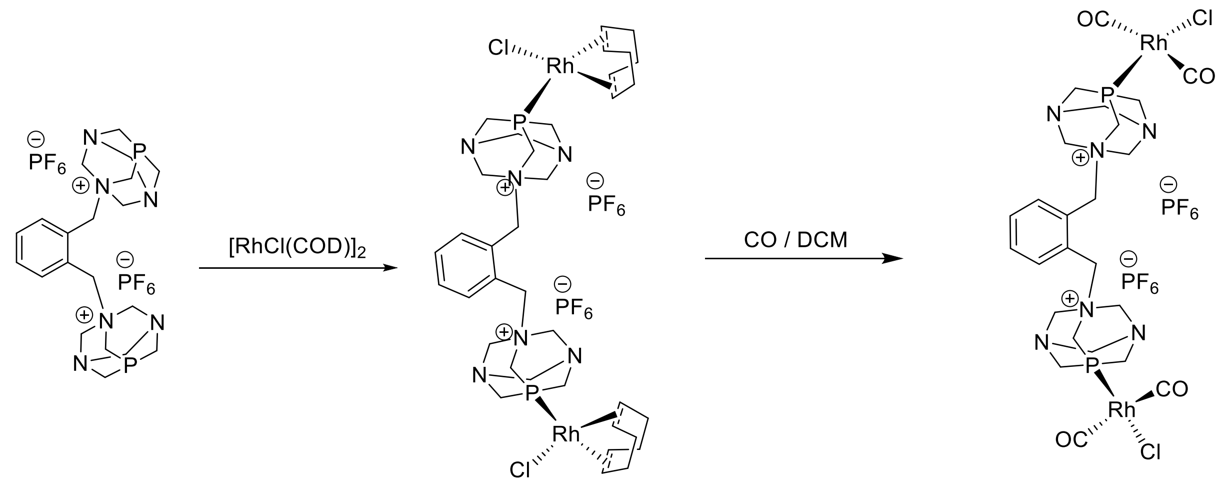
Scheme 1.7: Synthesis of the mononuclear Rh/PTA complex and its carbonyl analogue.[89,108]



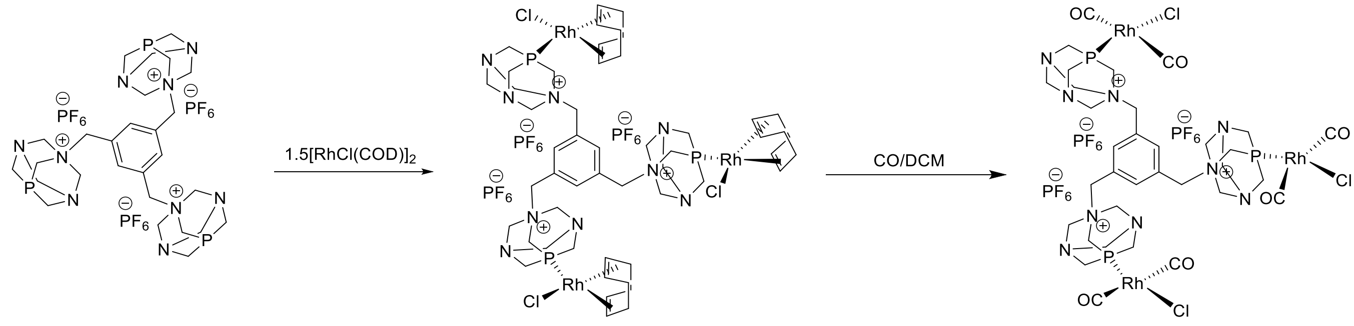
Scheme 1.8: Synthesis of some of the 1,4-dinuclear Rh/PTA complex and its carbonyl analogue.



Scheme 1.9: Synthesis of some of the 1,3-dinuclear Rh/PTA complex and its carbonyl analogue.



Scheme 1.10: Synthesis of some of the 1,2-dinuclear Rh/PTA complex and its carbonyl analogue.



Scheme 1.11: Synthesis of the trinuclear Rh/PTA complex and its carbonyl analogue.

- To evaluate the potential catalytic activity of the water-soluble rhodium complexes in biphasic hydroformylation reactions.

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Chapter 2

Synthesis and characterization of the mono-, di- and trimeric alkylated PTA ligands and the corresponding mono-, di- and trinuclear Rh(I)-PTA complexes

2.1 Introduction

Hydrofomylation is an extensively studied process and much attention has been given to the design and synthesis of new metal complexes that exhibit improved catalytic activity, greater product selectivity and can easily be reused.[1–5] New metal complexes which are used as catalysts for the hydroformylation reaction continue to be studied due to the need for simple and effective catalysts to facilitate catalytic reactions, and for easy recovery of the catalyst such as in the aqueous biphasic hydroformylation of olefins.[6,7]

Aqueous biphasic hydroformylation is one of the strategies employed in an attempt to tackle the challenge of separating the catalyst from the products after completion of the catalytic reaction.[8–13] The design and synthesis of water-soluble complexes is required because in the process of the aqueous biphasic hydroformylation catalytic reaction, the desired media for the catalyst precursors to be soluble in is water.[14,15] This allows for the retention of the catalyst precursor in the aqueous layer, affording easy separation from the organic product. This then allows for the catalyst precursor to be re-used.[16,17]

To improve the water-solubility of a metal complex, water-soluble ligands are co-ordinated to the metal centre.[6,18,19] Phosphine ligands are widely used as their steric and electronic properties can easily be tuned by using a variety of organic substituents.[10,20] 1,3,5-Triaza-7-phosphaadamantane (PTA) is a water-soluble phosphine which has been coordinated to a number of metal centres and the resulting complexes have been studied and shown to be suitable for use in various catalytic transformations.[21–23]

The water solubility of PTA comes about due to its nitrogen atoms forming hydrogen bonds with water.[24] PTA can be derivatised in a number of ways in an attempt to increase its water-solubility and to fine-tune its electronic properties. The thermal and chemical stability of PTA, together with its increased hydrophilicity when compared to the conventional phosphine ligands (PR_3),[25] makes it a ligand worth exploring.

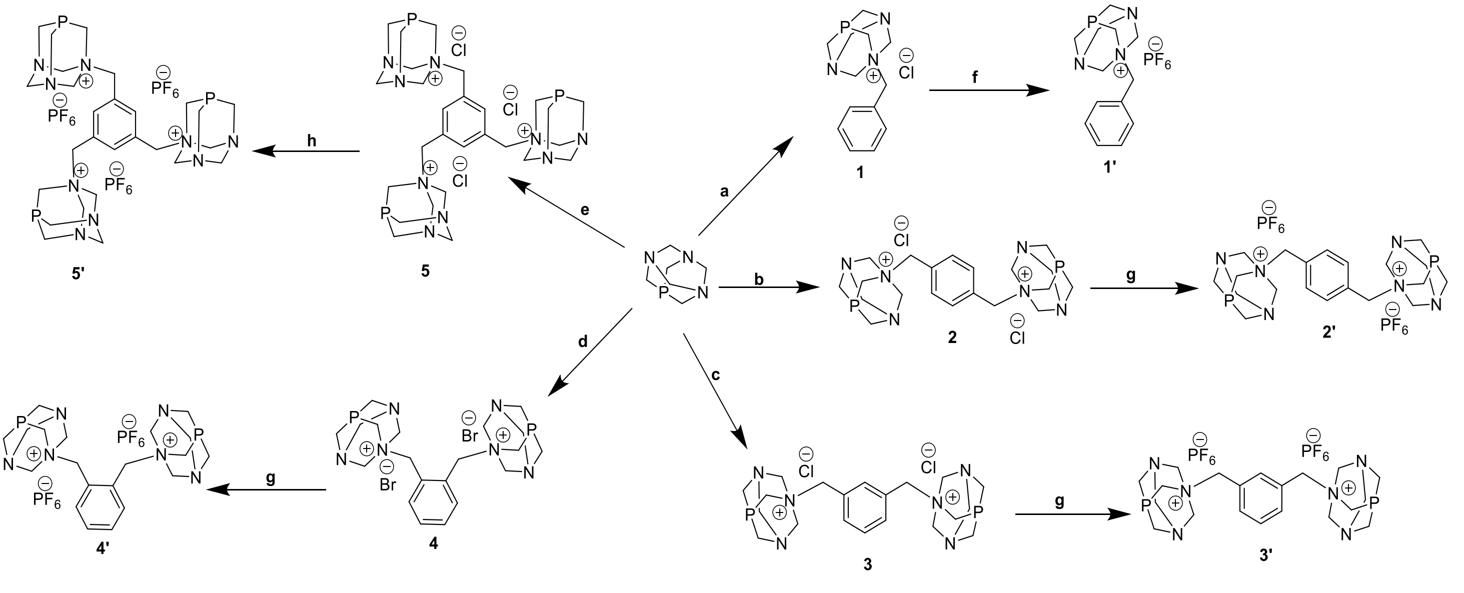
Just as the reusability of the catalysts is important, it is also important to improve on the activity and selectivity of the catalysts. Recent approaches to improving the activity and selectivity of catalysts have been directed to increasing the number of metal centres.[26–29] This idea stems from nature's own metalloenzymes, which possess more than one metal centre and have been reported to exhibit increased activity and selectivity.[30,31] This then prompted us to increase the number of metal centres present in our systems in an attempt to improve the catalytic activity and selectivity.

In this chapter, the syntheses and characterisation of a series of mono-, di- and trimeric PTA ligands and their subsequent mono-, di- and trinuclear rhodium(I) complexes is discussed.

2.2 Synthesis and Characterisation of the alkylated PTA ligands

*2.2.1 Synthesis and characterisation of ligands **1 – 5***

The benzylated PTA derivatives (**1** – **5**, Scheme 2.1) were prepared as previously described in literature.[32–34] The benzylic halides (benzyl chloride, 1,4-bis(chloromethyl)benzene, 1,3-bis(chloromethyl)benzene, 1,2-bis(bromomethyl)benzene and 1,3,5-tris(chloro–methyl)benzene) were reacted with appropriate equivalents of PTA to afford ligands **1**, **2**, **3**, **4** and **5** respectively (Scheme 2.1). The ligands were isolated in moderate to good yields (73 – 97 %) as white solids (**1** – **4**) and a beige solid (**5**). All ligands (**1** – **5**) exhibited good solubility in water at room temperature (200 – 1000 mg/mL). The signals in the ^{1}H NMR correlate with those reported in literature.[32–34]



a) Benzyl Chloride, MeOH, 70 °C, 2 h
b) 1,4-bis(chloromethyl)benzene, Acetone, 60 °C, 2 hrs
c) 1,3-bis(chloromethyl)benzene, Acetone, 60 °C, 2 hrs
d) 1,2-bis(bromomethyl)benzene, Acetone, 60 °C, 2 hrs
e) 1,3,5-tris(chloromethyl)benzene, Acetone, 60 °C, 18 hrs
f) NH_4PF_6 , EtOH, r.t., 20 hrs
g) NH_4PF_6 , EtOH, r.t., 72 hrs
h) NH_4PF_6 , EtOH, r.t., 96 hrs

Scheme 2.1: Syntheses of the monomeric, dimeric and trimeric ligands.

The ^{1}H NMR spectrum of ligand **1** (Figure 2.2) shows a multiplet at δ = 7.55 accounting for the aromatic protons, and the mono alkylation of PTA is confirmed by the splitting of the signals of the –CH$_2$ protons of PTA. Four signals are assigned to the –CH$_2$ protons of the PTA cage. Two multiplets at δ = 5.14 – 4.88 and 4.52 – 4.38 for the lower rim N-C**H$_2$**-N$^+$ and N-C**H$_2$**-N protons respectively, a doublet at δ = 4.28 and another mutliplet at δ = 3.94 – 3.76 for the upper rim P-C**H$_2$**-N$^+$ and P-C**H$_2$**-N protons respectively.

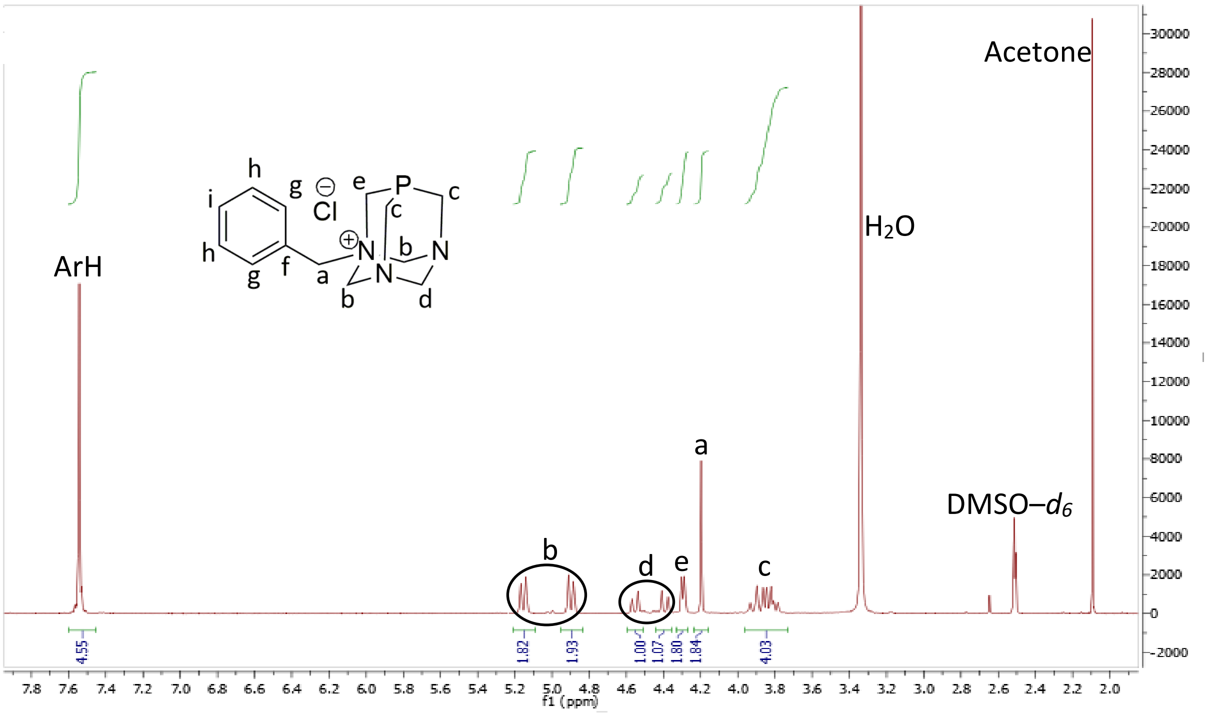


Figure 2.2: A full ^{1}H NMR spectrum (DMSO-*d*$_6$) of ligand **1**.

2D NMR (HSQC) spectroscopy (Figure 2.3) was utilised to aid in the identification of carbon signals in the structure of ligand **1**. The ^{13}C{^{1}H} NMR spectrum of ligand **1** (Figure 2.4) further confirms the alkylation of PTA. Four signals are observed for the PTA moiety as singlets at δ 79.10 and 69.79 ppm for N-**C**H$_2$-N$^+$ and N-**C**H$_2$-N respectively and doublets at δ = 57 87 for P-**C**H$_2$-N$^+$ and δ = 45.99 for P-**C**H$_2$-N. One singlet was observed in the ^{31}P{^{1}H} NMR spectrum (Figure 2.5) at δ = -82.74, confirming the presence of only one phosphorus species. Similar splitting patterns in the ^{1}H and ^{13}C{^{1}H} NMR spectra of ligands **2** – **5** are observed, confirming the alkylation of PTA. One singlet in each of the ^{31}P{^{1}H} NMR spectra of ligands **2** – **5** also confirm the presence of only one phosphorus entity for these ligands. The integration of the proton signals in the ^{1}H NMR spectrum of each of ligands **1** – **5** further confirms that ligand **1** is a monomeric ligand, **2** – **4** are dimeric ligands and **5** is a trimeric ligand with respect to PTA and that each PTA moiety is monoalkylated in all ligands.

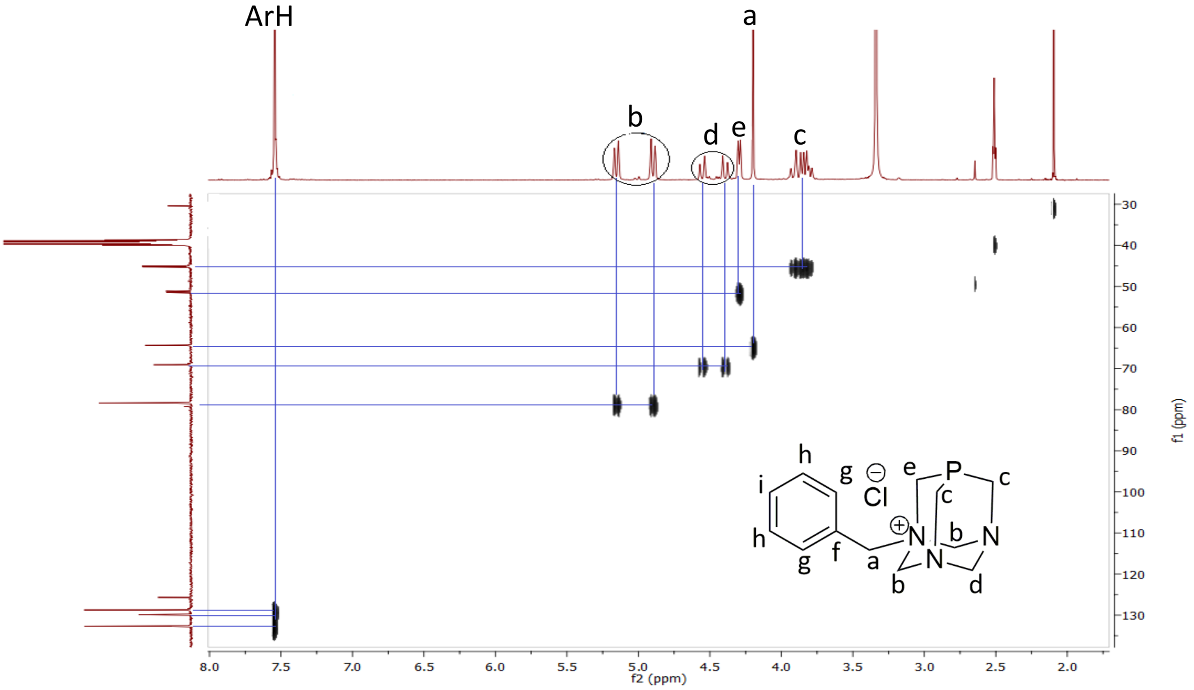


Figure 2.3: A full 2D NMR (HSQC) spectrum (DMSO-d_6) of ligand **1**.

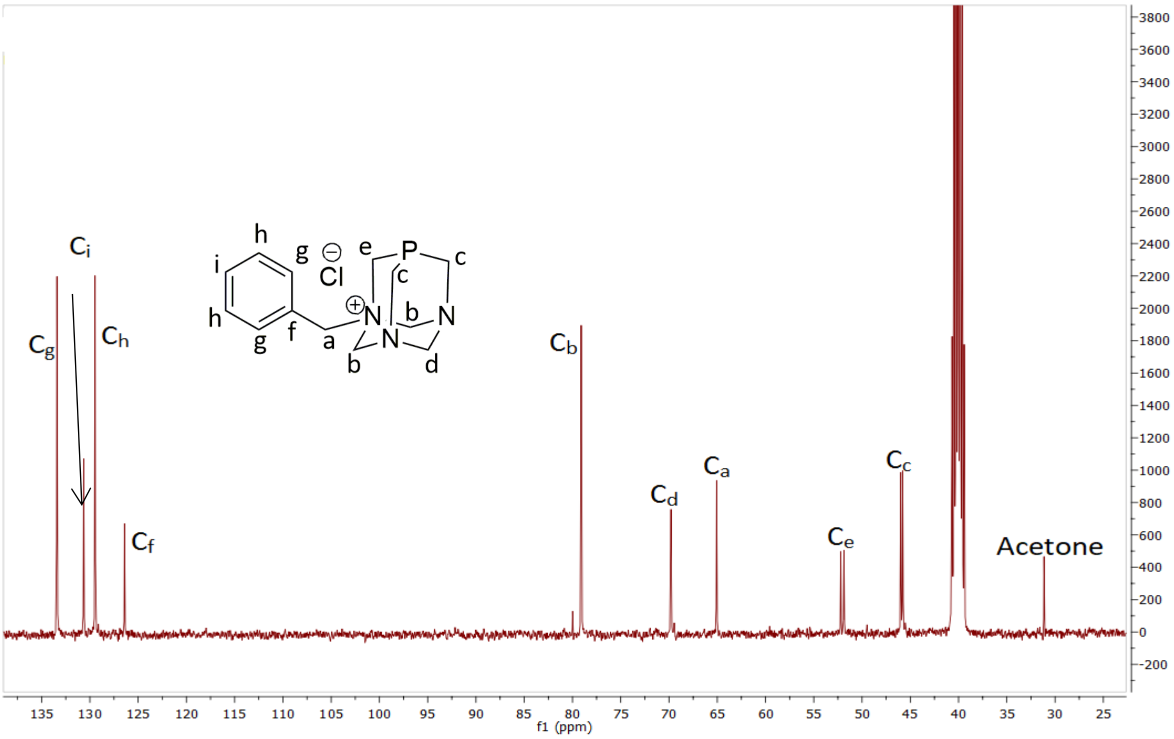


Figure 2.4: A full $^{13}C\{^{1}H\}$ NMR spectrum (DMSO-d_6) for ligand **1**.

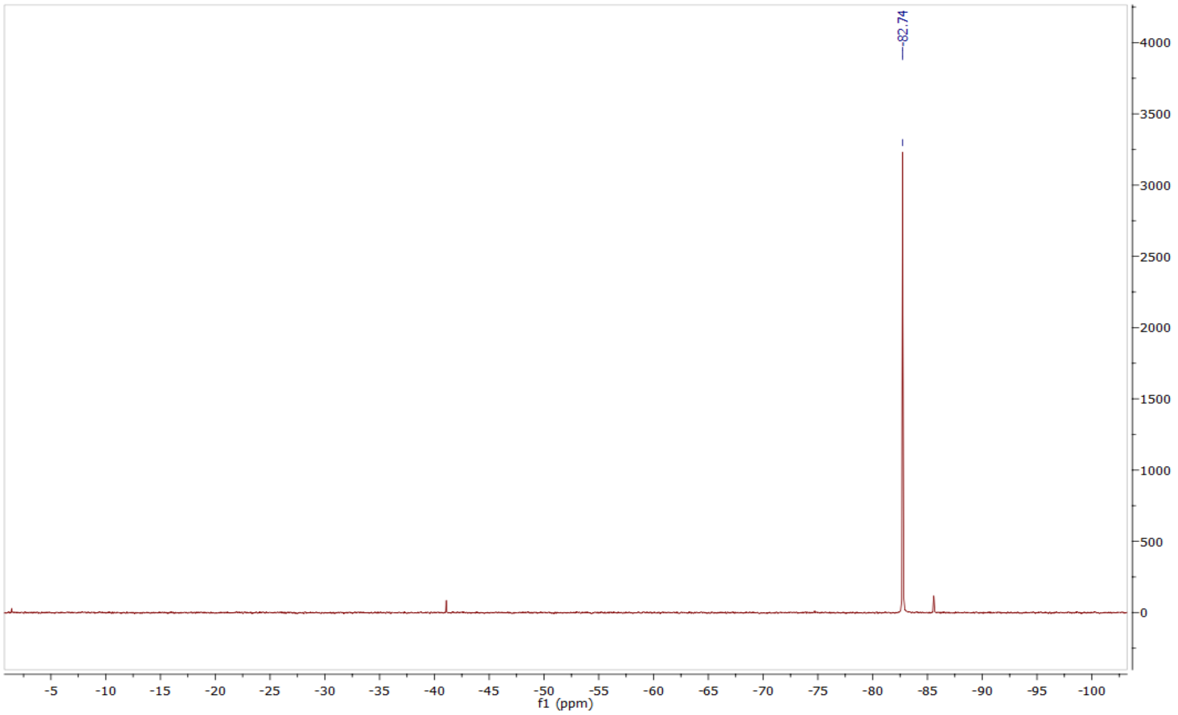


Figure 2.5: A full $^{31}P\{^{1}H\}$ NMR spectrum (DMSO-d_6) for ligand **1**.

*2.2.2 Synthesis and characterisation of ligands **1’** – **5’***

Initial complexation reactions were attempted by reacting each of ligands **1** - **5** with the appropriate equivalents of the $[RhCl(COD)]_2$ dimer and the resulting products were found to be unstable. Counterion exchange was then performed, replacing the chlorido anions with the much larger hexaflurophosphate anions. Ligands **1’**, **2’**, **3’**, **4’** and **5’** were prepared by reacting each of ligands **1**, **2**, **3**, **4** and **5** with the appropriate equivalent of NH_4PF_6 in ethanol (Scheme 2.1) and were obtained as white solids in moderate to good yields (76 – 94 %).

^{1}H NMR spectra of the ligands show a slight upfield shift of the PTA proton signals when compared to the ^{1}H NMR spectra of ligands **1** – **5** (Figure 2.6). The $^{31}P\{^{1}H\}$ NMR spectra of ligands **1’** – **5’** further confirms successful anion exchange. Two signals, accounting for two phosphorus entities, are observed in the $^{31}P\{^{1}H\}$ NMR spectra of each of ligands **1’** – **5’**, the signal corresponding to the PTA phosphorus entity (which shifts upfield) and a septet for the PF_6^- phosphorus entity. Unfortunately, the substitution of the chlorido anions for the hexaflurophosphate anions led to a drastic decrease in the water-solubility of the ligands. The water-solubility of each of ligands **1’** – **5’** is *ca.* 5mg/mL at room temperature.

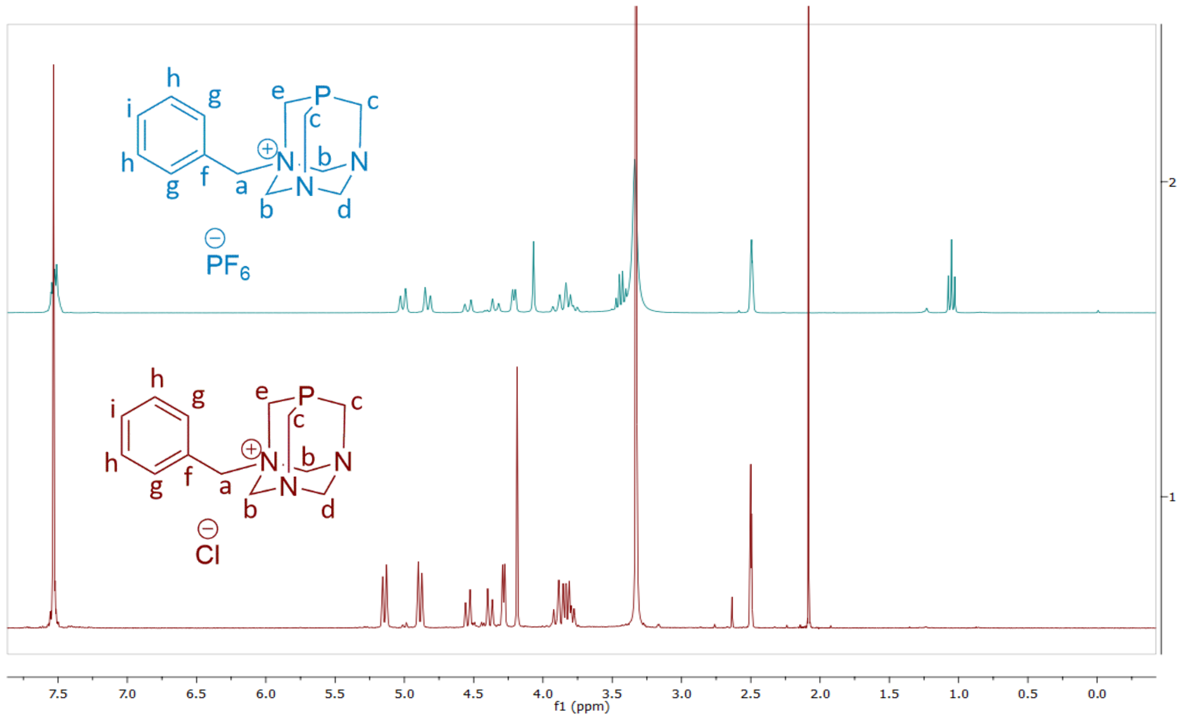
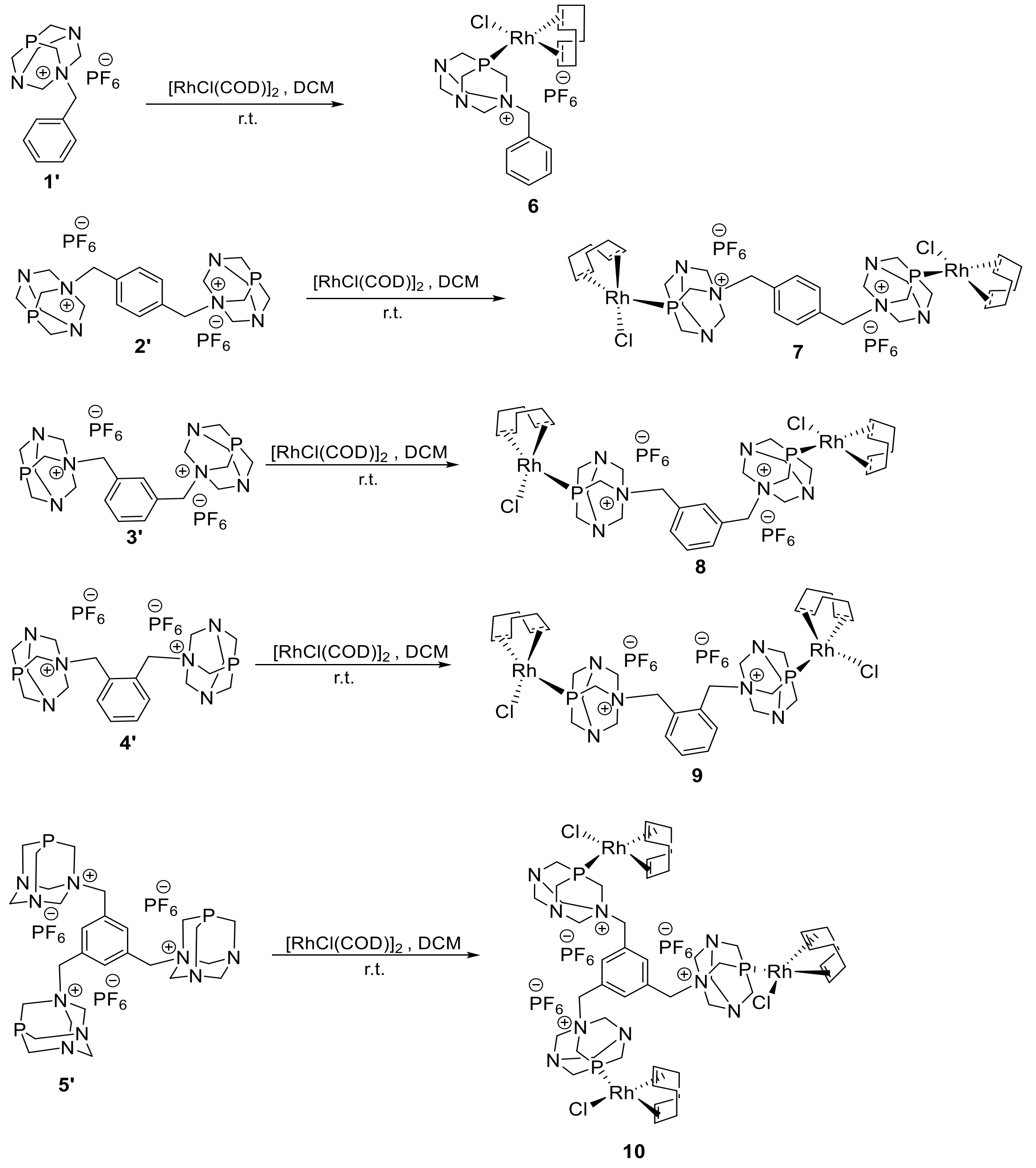


Figure 2.6: The stacked ^{1}H NMR spectra (DMSO-d_6) of the monomeric ligand before and after the counter ion exchange.

2.3 Synthesis and characterisation of mono-, di- and trinuclear Rh-PTA complexes

*2.3.1 Synthesis and characterisation of COD analogues of the mono-, di- and trinuclear Rh-PTA complexes **6 – 10***

The mononuclear, 1,4-dinuclear, 1,3-dinuclear, 1,4-dinuclear and the trinuclear complexes (Scheme 2.2) were prepared in order to investigate the effect of increasing the number of metal centres on the activity and selectivity when used as pre-catalysts in the hydroformylation of 1-octene.



Scheme 2.2: Synthesis of mono-, di- and trinuclear Rh-PTA catalyst precursors.

Ligands **1’** – **5’** were each reacted with appropriate equivalents of the $[RhCl(COD)]_2$ dimer to afford complexes **6**, **7**, **8**, **9** and **10** respectively. The complexes were obtained as yellow solids in good yields (61 – 94 %). The metal complexes are insoluble in water at room temperature; this is attributed to the highly hydrophobic PF_6^- counterions. Solubility studies conducted at 40 °C in water posted an average solubility of 2mg/mL for complexes **6** – **10**.

Coordination of the ligands to the metal centre is confirmed by three new signals in the ^1H NMR spectrum of each of complexes **6** – **10** accounting for the COD protons. Figure 2.7 shows the ^1H NMR of complex **6**. A general downfield shift of the PTA proton signals is observed when compared to the ^1H NMR spectrum of ligand **1'**. Coordination of ligand **1'** *via* the phosphorus atom is further corroborated by the absence of the PTA phosphorus signal at δ = -83.50 in $^{31}P\{^1H\}$ NMR (Figure 2.8). Furthermore, a doublet is observed at δ = -32.67 ppm with coupling constant J_{Rh-P} = 136.0 Hz. A singlet at δ = -4.33 in the $^{31}P\{^1H\}$ NMR of complex **6** is also observed, and is presumed to be a phosphine oxide signal as PTA phosphine oxide signals occur between 0 – -10 ppm. [35–37] The ^1H and $^{31}P\{^1H\}$ NMR spectra of complexes **7** – **10** exhibit similar shifts and changes as complex **6** when compared to the ^1H and $^{31}P\{^1H\}$ NMR spectra of their corresponding ligands.

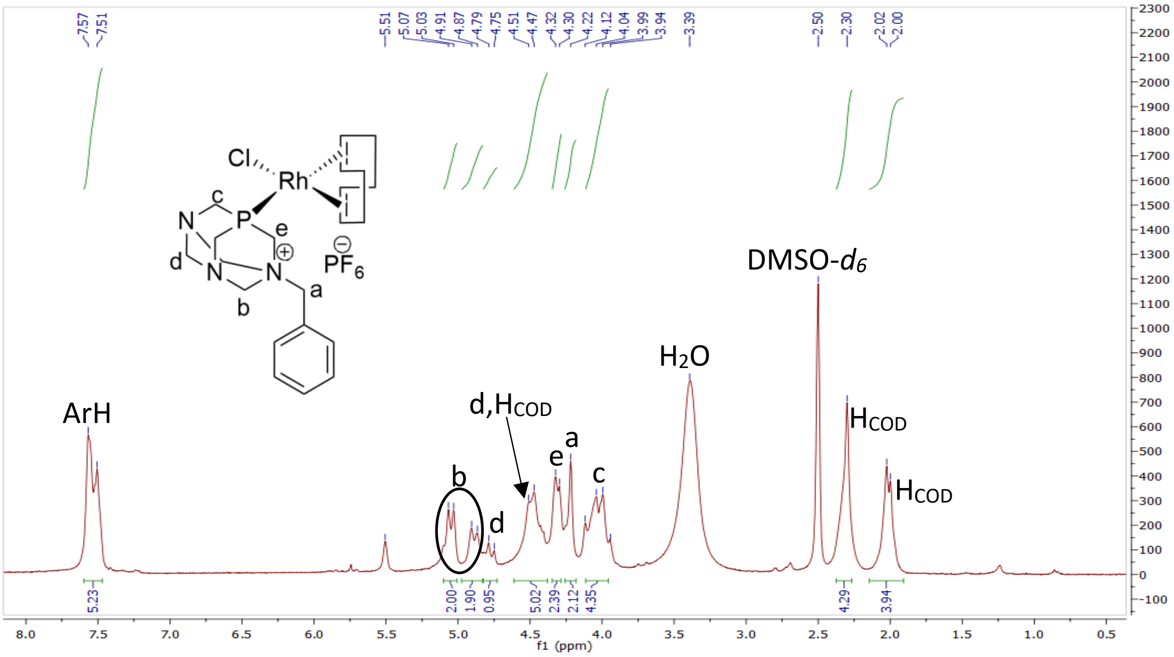


Figure 2.7: A full ^1H NMR spectrum (DMSO-d_6) for complex **6**.

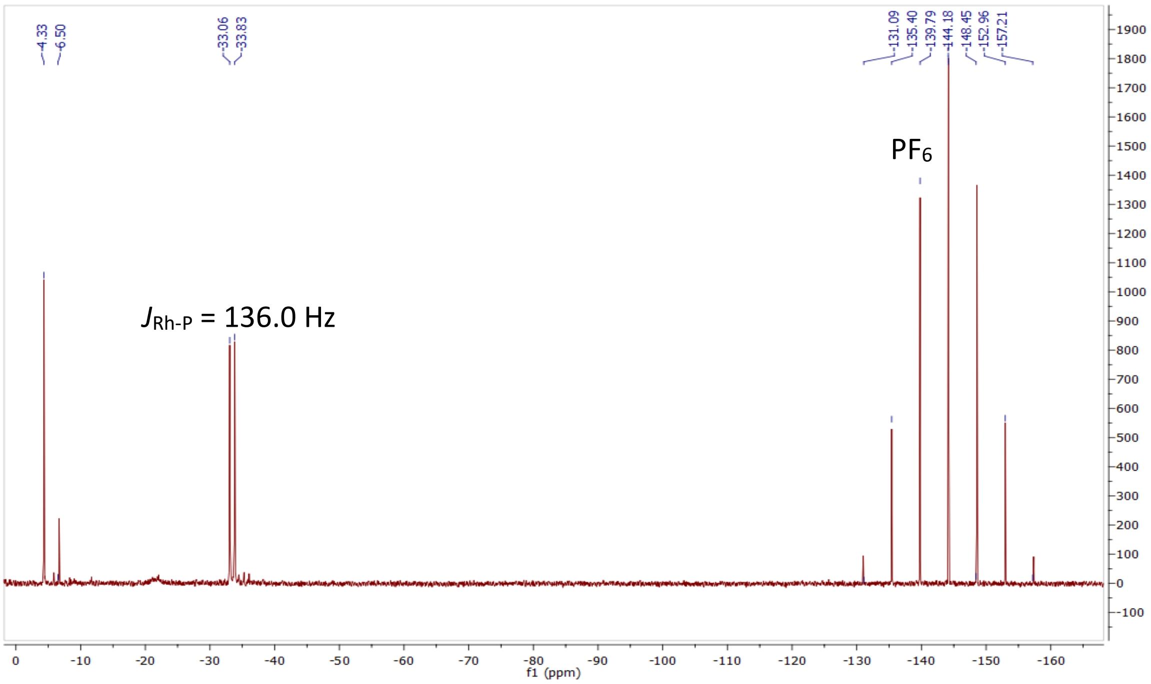
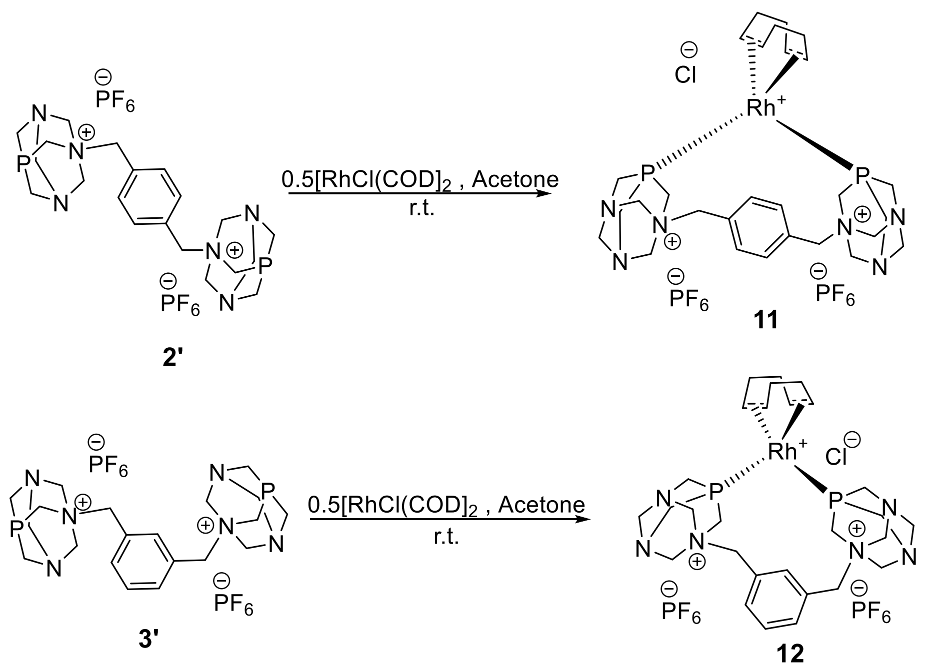


Figure 2.8: A full $^{31}P\{^1H\}$ NMR spectrum (DMSO-d_6) for complex **6**.

The ESI-MS(+) spectrum for complex **6** shows a base peak at *m/z* 264.1263 corresponding to $[M–PF_6+Na]^{2+}$. Base peaks are observed at *m/z* 312.9192, 312.1030 and 312.1024 for complexes **7**, **8** and **9** respectively, each corresponding to $[M–2PF_6+Na]^{3+}$. The ESI-MS(+) spectrum for complex **10** shows a base peak at *m/z* 476.9400 corresponding to $[M–3PF_6]^{3+}$.

*2.3.2 Synthesis and characterisation of COD analogues of the mononuclear chelate complexes **11** – **12***

The synthesis of the mononuclear complexes where the dimeric ligands **2’**, **3’** and **4’** behave as bidentate chelating ligands was explored (Scheme 2.3). This was done in order to compare the catalytic activity of the resulting mononuclear chelating complexes to that of the mononuclear complex (that coordinates in a monodentate fashion) obtained from the monomeric ligand **1’**. The chelate complexes are expected to have different electronic properties i.e. less electron density around the metal centre compared to the mononuclear complex obtained using ligand **1’** and, possibly, different catalytic activities.



Scheme 2.3: Synthesis of the mononuclear chelate Rh-PTA complexes.

Each of ligands **2’**, **3’** and **4’** were reacted with 1 equivalent of the $[RhCl(COD)]_2$ dimer. The 1,4-mononuclear (**11**) and 1,3-mononuclear (**12**) complexes were obtained as yellow solids in excellent yields (90 and 88 % respectively). The 1,2-mononuclear complex was not successfully synthesised, despite stirring the reaction solution for long periods of time and elevating the temperature at which the reaction was conducted. The reaction between ligand **4’** and 1 equivalent of the $[RhCl(COD)]_2$ dimer resulted in a mixture of the 1,2-dinuclear complex **9** and unreacted ligand. Failure to synthesise the 1,2-mononuclear could be attributed to the bulkiness of the PTA moiety hence restricting the ligand from behaving as a chelate ligand.

The ^{1}H and $^{31}P\{^{1}H\}$ NMR spectra confirm the formation of both complexes **11** and **12**. Integration of the signals in the ^{1}H NMR spectrum of complex **12** (Figure 2.9) shows that there is one COD ligand per 1,3-dimeric ligand, suggesting that the desired product was synthesised. Formation of the chelating complex **12** is further confirmed by $^{31}P\{^{1}H\}$ NMR spectrum (Figure 2.10) as no free PTA phosphorus signal is observed at *ca.* δ = -80 and a doublet is observed at δ = -33.34 with coupling constant $J_{Rh\text{-}P}$ = 125.6 Hz. Similar splitting patterns were observed in the ^{1}H and $^{31}P\{^{1}H\}$ NMR spectra of complex **11**. The ESI-MS(+)

spectrum shows base peaks at *m/z* 157.0349 and 157.0352 for complexes **11** and **12** respectively, both corresponding to $[M{-}2PF_6{-}Cl{+}Na]^{4+}$.

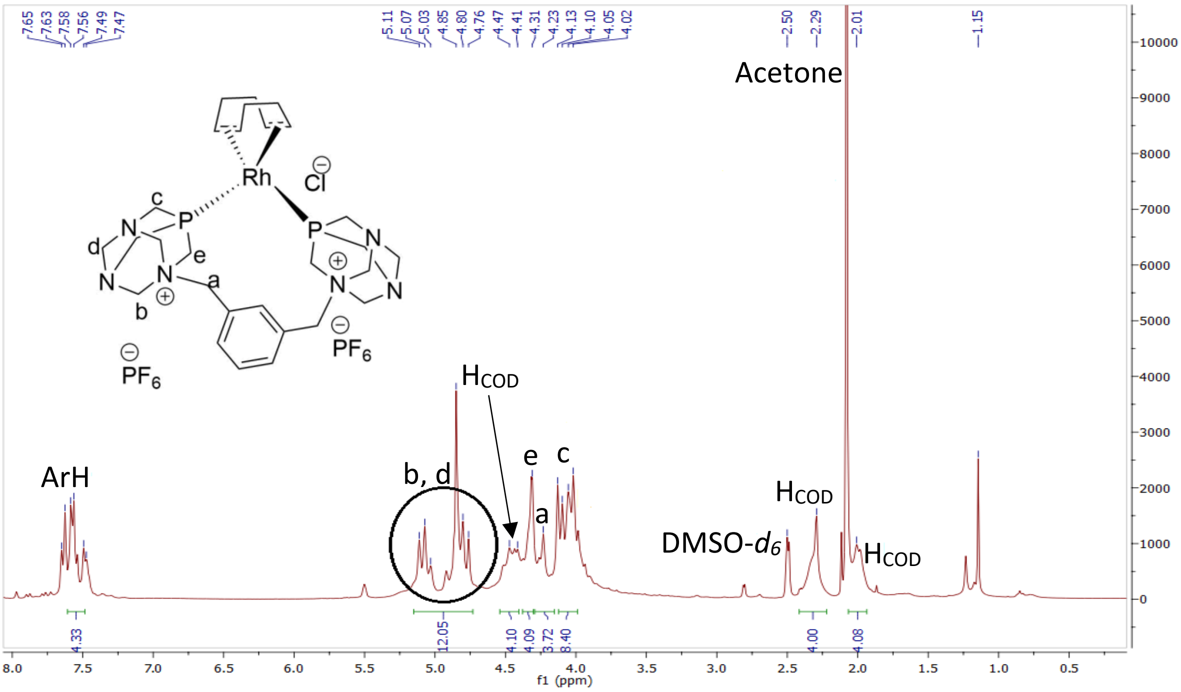


Figure 2.9: A full ^1H NMR spectrum (DMSO-d_6) for complex **12**.

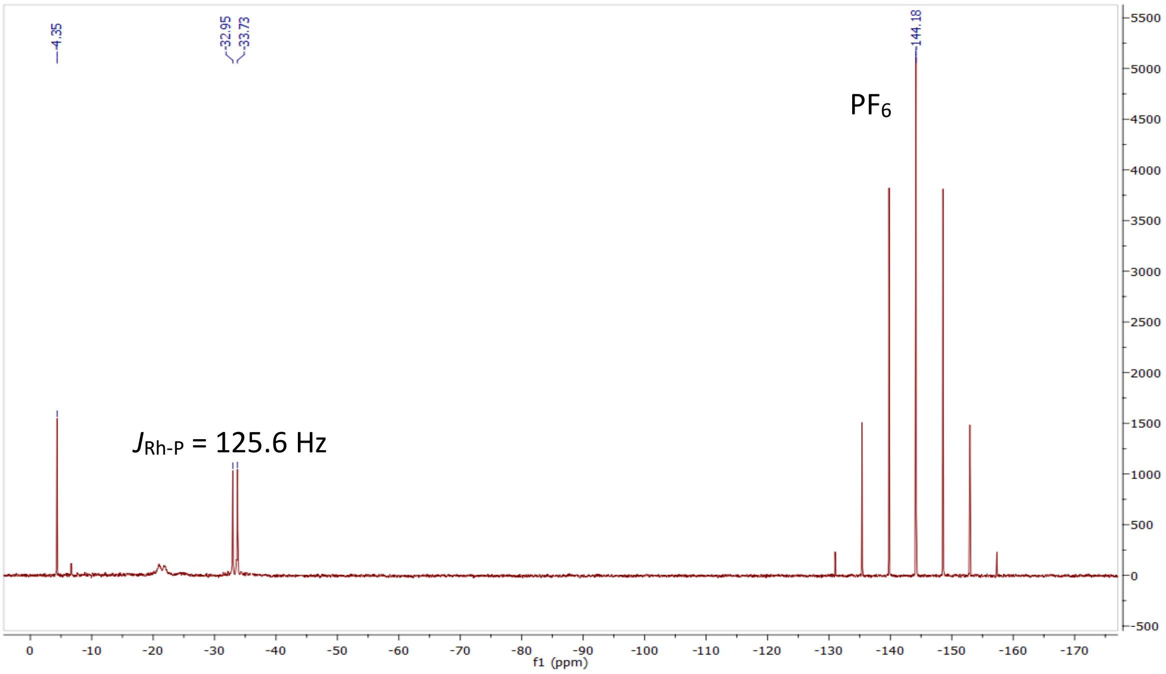
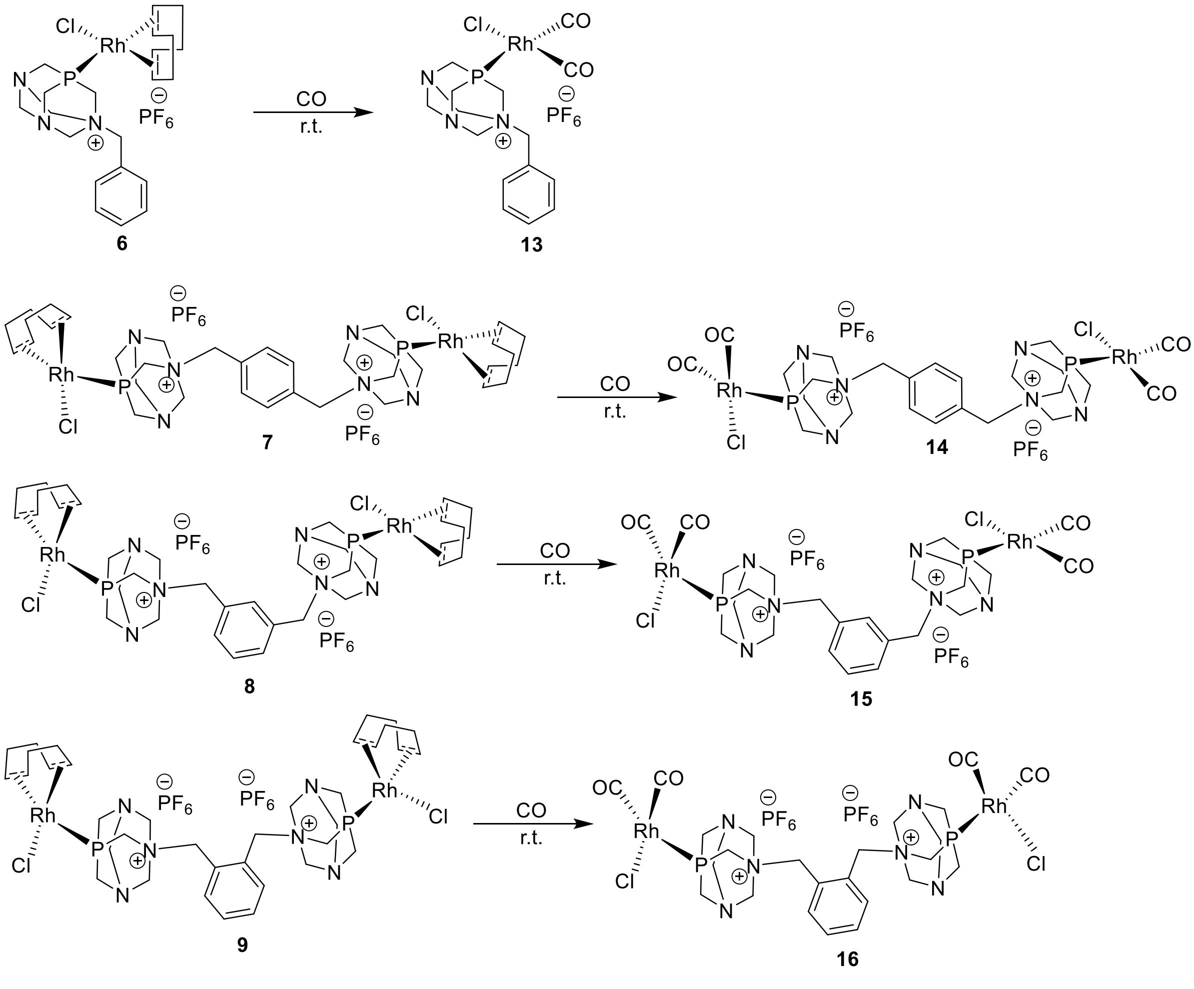


Figure 2.10: A full $^{31}P\{^1H\}$ NMR spectrum (DMSO-d_6) for complex **12**.

*2.3.3 Synthesis and characterisation of CO analogues of the mono-, di- and trinuclear Rh-PTA complexes **13** – **18***

The carbonyl (CO) analogues of the Rh-PTA complexes **6** – **12** were synthesised according to published literature methods with minor modifications (Scheme 2.4).[38–40] The rationale for the preparation of these complexes is based on the different electronic and steric properties arising from the COD and CO ligands. CO is a good π-acceptor and hence electron density can be back-donated from the metal centre to the CO ligand, relieving the metal centre of electron density. Thus, the electron density around the metal centre of the complexes bearing the CO ligands is expected to be less than the electron density around the metal centre of the complexes bearing the COD ligands. Moreover, CO is a less bulky ligand than the COD ligand and would possibly influence the regioselectivity of the catalytic reaction in a different manner to the COD ligand.



Scheme 2.4: Synthesis of CO analogues of the Rh-PTA complexes.

Each of complexes **6** – **9** were reacted with gaseous CO (Scheme 2.4) to afford complexes **13** – **16** as light orange solids in good to excellent yields (70 – 98 %). Despite several attempts under varying conditions, including increasing the temperature and CO pressure, the CO analogue of the trinuclear complex **10** could not be successfully isolated. This could be due to the poor solubility of complex **10** in most organic solvents.

The successful synthesis of complex **13** was confirmed by the absence of the COD proton signals and the slight upfield shift of the PTA proton signals in the ^{1}H NMR spectrum (Figure 2.11). ^{13}C{^{1}H} NMR spectrum further confirms the formation of complex **13**. A signal is observed at δ = 192.08 assigned to the CO ligands. The signal corresponding to the PTA phosphorus entity in ^{31}P{^{1}H} NMR also shows an upfield shift indicating successful substitution of the COD ligand for the CO ligands.

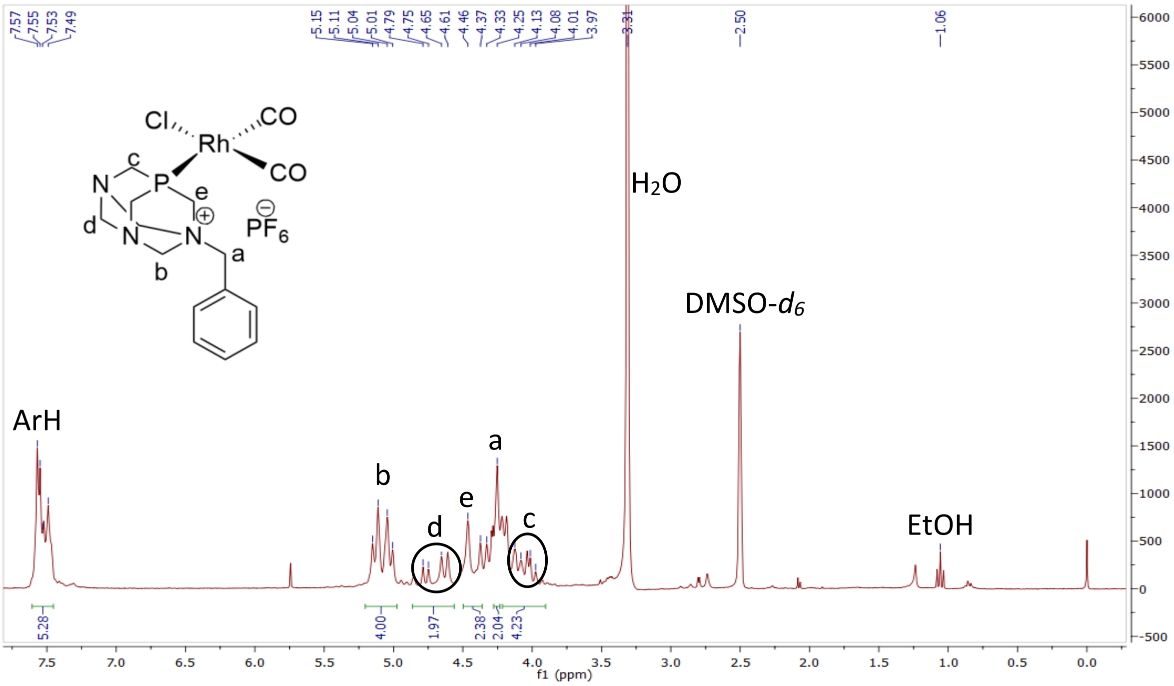


Figure 2.11: A full ^{1}H NMR spectrum (DMSO-d_6) for complex **13**.

Infrared (IR) spectroscopy (Figure 2.12) further corroborates the substitution of the COD ligand with the CO ligands. The presence of two *v*(C≡O) absorption bands at 2048 and 1996 cm^{-1} suggest that the two CO ligands are in different chemical environments. The two CO ligands are *cis* to each other in the solid state, i.e. one is *trans* to the Cl ligand and the other is *trans* to the PTA ligand. Similar shifts in the ^{1}H, ^{13}C and ^{31}P NMR spectra and similar IR patterns were also observed for complexes **14**, **15** and **16**.

The ESI-MS(+) spectrum for complex **13** shows a base peak at *m/z* 248.1313 corresponding to $[M{-}PF_6{+}Na]^{2+}$. Base peaks are observed at *m/z* 268.1862 $[M{-}2PF_6{+}H]^{3+}$, 268.0205 $[M{-}2PF_6{+}H]^{3+}$ and 276.1263 $[M{-}2PF_6{+}Na]^{3+}$ for complexes **14**, **15** and **16** respectively.

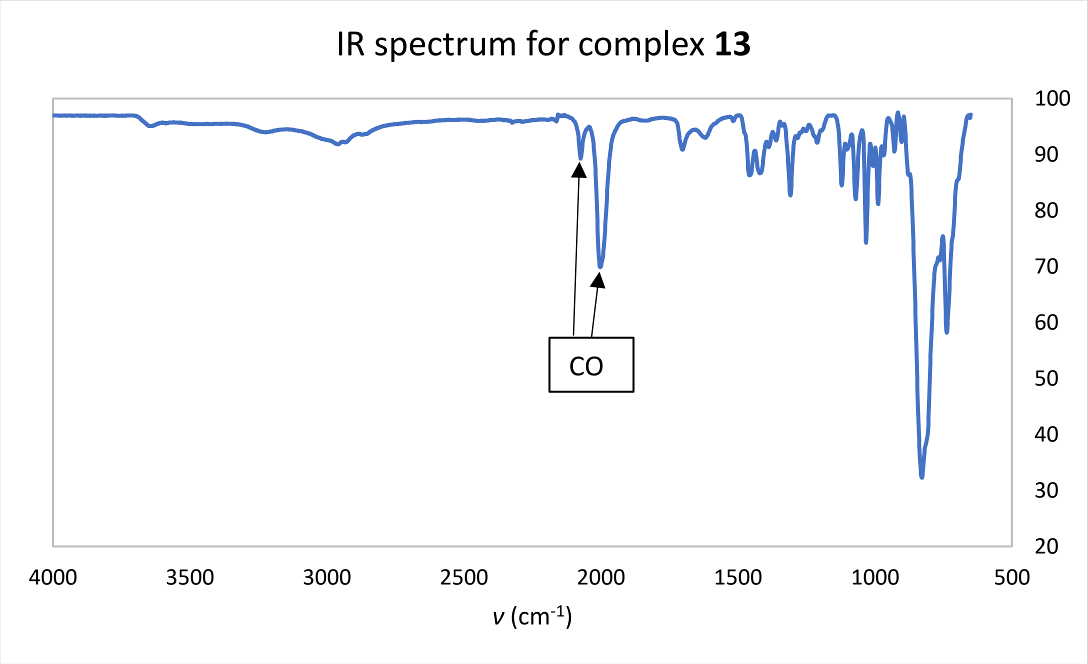
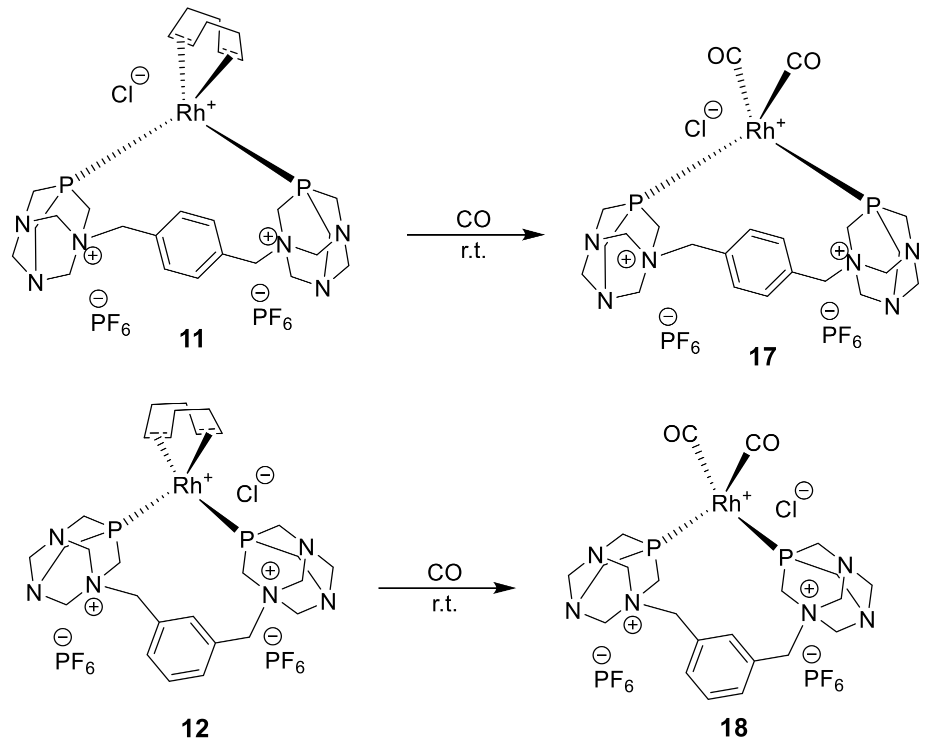


Figure 2.12: FT-IR spectrum of complex **13**.

CO analogues of the chelate complexes (Scheme 2.5) were synthesised by reacting each of complex **11** and **12** with CO gas to give complexes **17** and **18** as light orange solids in good yield (86 and 87 % respectively).



Scheme 2.5: Synthesis of the CO analogues of the mononuclear chelate complexes.

The shifts of the signals in the ^{1}H, $^{13}C\{^{1}H\}$ and $^{31}P\{^{1}H\}$ NMR spectra were similar to those of complexes **13** – **16**. IR spectroscopy shows a *v*(C≡O) absorption band for each chelating complex corresponding to the overlapping bands of the two CO ligands. The absorption band is observed at 1998 cm^{-1} for complex **17** and at 1996 cm^{-1} for complex **18** (Figure 2.13 shows the IR spectrum of complex **17**). The ESI-MS(+) spectrum shows base peaks at *m*/*z* 188.0950 and 188.0943 for complexes **17** and **18** respectively, both corresponding to $[M{-}2PF_6{-}Cl]^{3+}$.

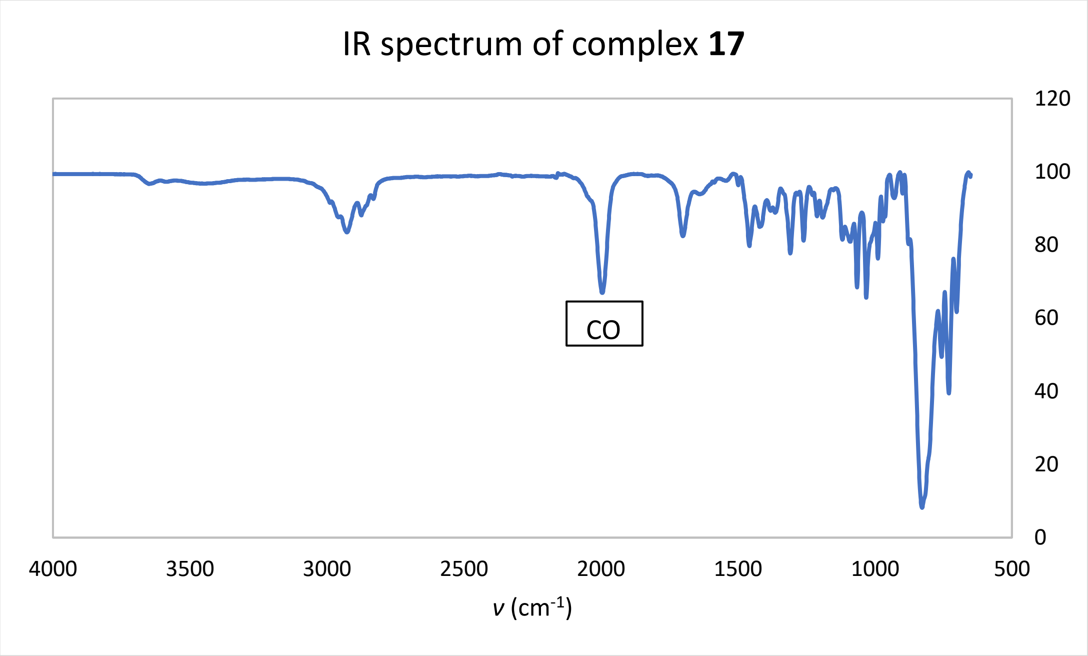


Figure 2.13: FT-IR spectrum of complex **17**.

2.4 Summary

A series of mono-, di- and trimeric alkylated PTA ligands were synthesised. These ligands were used to successfully synthesise mono-, di- and trinuclear Rh-PTA COD complexes and their CO analogues. Despite several attempts under varying conditions, the 1,2-mononuclear chelating complex (both the COD and CO analogues) and the Carbonyl analogue of the trinuclear Rh-PTA complex could not be successfully isolated. The ligands and complexes that were successfully synthesised and isolated were characterised using spectroscopic and analytical techniques which include; ^{1}H NMR, $^{13}C\{^{1}H\}$ NMR and $^{31}P\{^{1}H\}$ NMR spectroscopy, FT-IR spectroscopy, mass spectrometry as well as elemental analysis.

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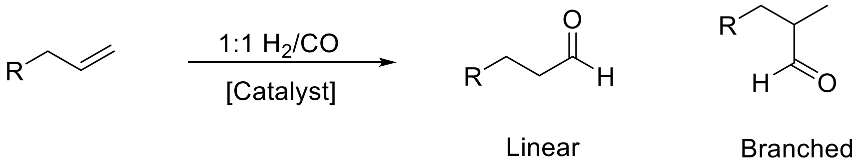
Chapter 3

Catalytic evaluation of the water-soluble mono-, di- and trinuclear Rh(I)-PTA complexes in the aqueous biphasic hydroformylation of 1-octene.

3.1 Introduction

Hydroformylation is the reaction of alkenes with carbon monoxide and hydrogen gases to yield aldehydes (Scheme 3.1).[1] While aldehydes are the most desired products of this reaction, side products of isomerisation (iso-alkenes) and hydrogenation (alkanes and alcohols) may also be formed. The alcohols produced can be used to manufacture detergents or as solvents.[2,3] Since the discovery of the hydroformylation reaction by Otto Roelen in 1938,[4] it has been one of the most important chemical transformations, producing over 12 million tons of aldehydes per annum.[5–8] The hydroformylation reaction occurs in the presence of a homogeneous catalyst bearing metals such as Co, Rh, or Ru, for example.[9,10] Rhodium complexes are commonly employed for this catalytic transformation as they exhibit improved activity and selectivity under mild reaction conditions.[11–14] However, due to rhodium being one of the most expensive and fast depleting metals, recovery and, consequently, recyclability of the Rh complexes is of great importance.



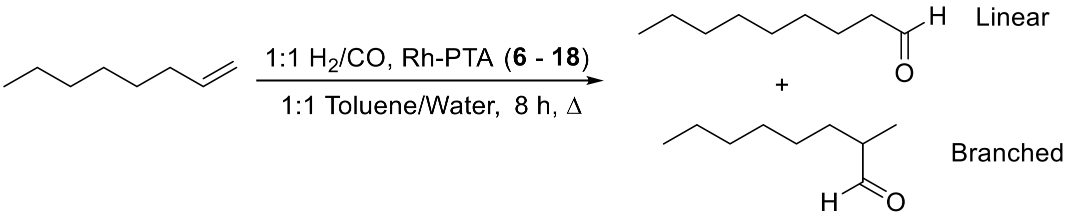
Scheme 3.1: Hydroformylation of alkenes.

A number of strategies have been developed over the years to allow for recovery of the metal catalyst.[15–17] These include the immobilisation of the metal catalyst using aqueous-organic biphasic media. This allows for the homogeneous catalyst to be 'heterogenised' with respect to the organic reactants and products, leading to facile recovery by decantation.[18–20] Aqueous biphasic hydroformylation is of great interest to scientists as it is economically viable due to water being abundant. Furthermore, the use of water is in line with Green Chemistry principles.[21,22] This leads to the need to design and synthesise complexes to be employed as pre-catalysts in the aqueous biphasic hydroformylation of olefins. These complexes have to be retained in the aqueous phase (thus, easily recovered) but not compromise on the activity and selectivity.

Recent efforts in improving the activity and selectivity of metal catalysts include increasing the number of metal centres the catalyst possesses. This is motivated by improved activities and selectivities exhibited by metalloenzymes which possess more than one metal centre.[23–25] The presence of two or more metal centres may lead to cooperativity between any two of the metal centres, therefore leading to greater activity and selectivity.[26–29] In this study, the performance of a series of water-soluble mono-, di- and trinuclear Rh(I)-PTA metal complexes was evaluated in the aqueous biphasic hydroformylation of 1-octene.

3.2 Aqueous biphasic hydroformylation of 1-octene

Complexes **6** – **18** were evaluated as catalyst precursors in the aqueous biphasic hydroformylation of 1-octene to form aldehydes as major products (Scheme 3.2).



Scheme 3.2: Aqueous biphasic hydroformylation of 1-octene.

A stainless steel pipe reactor was charged with the substrate (1-octene) and the internal standard (*n*-decane) dissolved in 5mL toluene and either one of catalyst precursors **6** – **18** in 5 mL water. The pipe reactor was then heated and pressurised to the desired temperature and pressure. At the end of the catalytic reaction, the reactor was cooled and the organic products separated from the catalyst by decantation and analysed using gas chromatography.

3.2.1 Optimisation of the reaction conditions

The mononuclear (**6**), 1,4-dinuclear (**7**) and the trinuclear (**10**) complexes (Figure 3.1) were utilised for the initial catalytic studies in order to determine optimal conditions for the aqueous biphasic hydroformylation of 1-octene.

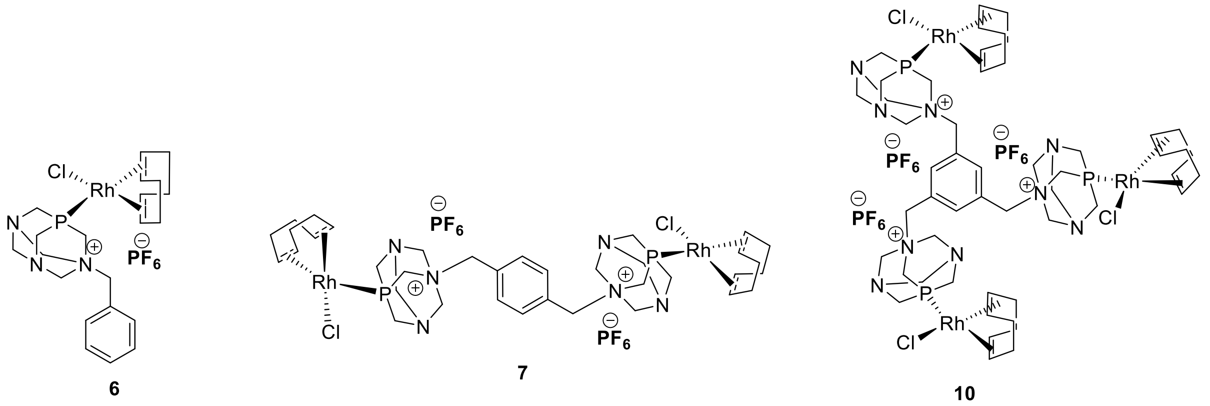


Figure 3.1: The complexes used for the determination of optimum conditions.

The optimisation reactions were performed at temperatures between 50 – 95 °C and pressures varied between 20 and 40 bar of syngas (CO:H_2 = 1:1), as shown in Table 3.1. The selection of these conditions was based on the conditions used for rhodium catalysed hydroformylation of terminal olefins reported in literature.[15,30,31] All catalytic reactions were carried out in duplicate for 8 hours. The catalyst loading was maintained at 2.87×10^{-4} mol% with respect to the rhodium metal centre (Rh:substrate = 1:2500) for each catalyst precursor.

Table 3.1: Hydroformylation results of 1-octene after 8 hours.[i]

Entry	Complex	Pressure (bar)	Temperature (°C)	Conversion (%)[a]	Aldehydes (%)[b]			Iso-octenes (%)[b]	*n*:iso[c]	TOF (h^{-1})[d]
					Total	linear	branched			
1	**6**	20	50	10	67	68	32	33	2.1	22
2		20	75	95	46	60	40	54	2.6	102
3		20	95	98	42	55	45	58	1.2	130
4		30	50	10	77	65	35	23	1.9	24
5		30	75	98	69	59	41	31	1.4	212
6		30	95	96	45	52	48	55	1.9	136
7		40	50	17	80	64	36	20	1.8	41
8		40	75	99	93	52	48	7	1.1	288
9		40	95	99	94	46	54	6	0.8	292
10	**7**	20	50	16	63	68	32	37	2.1	31
11		20	75	97	55	63	37	45	2.1	125
12		20	95	99	50	41	59	50	0.7	195
13		30	50	22	78	68	32	22	2.1	44
14		30	75	98	74	59	41	26	1.4	227
15		30	95	99	63	43	57	37	0.8	241
16		40	50	26	71	62	38	29	1.7	57
17		40	75	98	75	61	39	25	1.6	206
18		40	95	99	80	42	58	20	0.7	247
19	**10**	20	50	48	63	68	32	37	2.1	91
20		20	75	98	61	55	45	39	1.2	187
21		20	95	96	67	40	60	33	0.7	199
22		30	50	50	83	65	35	17	1.9	121
23		30	75	99	79	52	48	21	1.1	255
24		30	95	99	76	42	58	24	0.7	245
25		40	50	51	82	62	38	18	1.7	122
26		40	75	98	91	52	48	9	1.1	278
27		40	95	98	91	44	56	9	0.8	263

[i] Reactions carried out in toluene (5 mL) and distilled water (5 mL) with 7.18 mmol of 1-octene and 2.87×10^{-3}, 1.44×10^{-3} and 9.57×10^{-4} mmol of each of catalyst precursors **6**, **7** and **10** respectively varying the temperature (50, 75 and 95 °C) and pressure (20, 30 and 40 bar) of syngas ($CO:H_2$ = 1:1). GC conversions were obtained using *n*-decane as an internal standard in relation to authentic standard *iso*-octenes and aldehydes. TOF = (mol product/mol catalyst)h^{-1} and is based on total aldehydes. Average error estimates: [a]±2.1, [b]±1.5, [c]±0.1 % and [d]±4.2 %

Effect of temperature and pressure on conversion.

To study the effect of temperature and pressure on the conversion of 1-octene when complexes **6**, **7** and **10** are used as catalyst precursors, the reactions were carried out at 50, 75 and 95°C and at each temperature the pressure was changed to 20, 30 and 40 bar. The reactions were carried out while keeping all other reaction conditions (i.e. substrate amount, catalyst loading and reaction time) constant.

At 50 °C, all three catalyst precursors exhibit low conversion, with complex **10** showing the highest conversion of 51 % at 40 bar (Entry 25, Table 3.1). The conversion of 1-octene largely increases (>90 % in general) when the reactions are carried out at higher temperatures of 75 and 95 °C (Table 3.1). This is expected as the rate of a catalytic reaction increases with an increase in temperature, thus increasing the catalytic activity.[32,33] At high temperatures (75 and 95 °C), an increase in the pressure does not exhibit any significant effect on the conversion of 1-octene for each catalyst precursor used. The complexes reach near-quantitative conversion after 8 hours at high temperature independent of the syngas pressure applied (Figure 3.2).

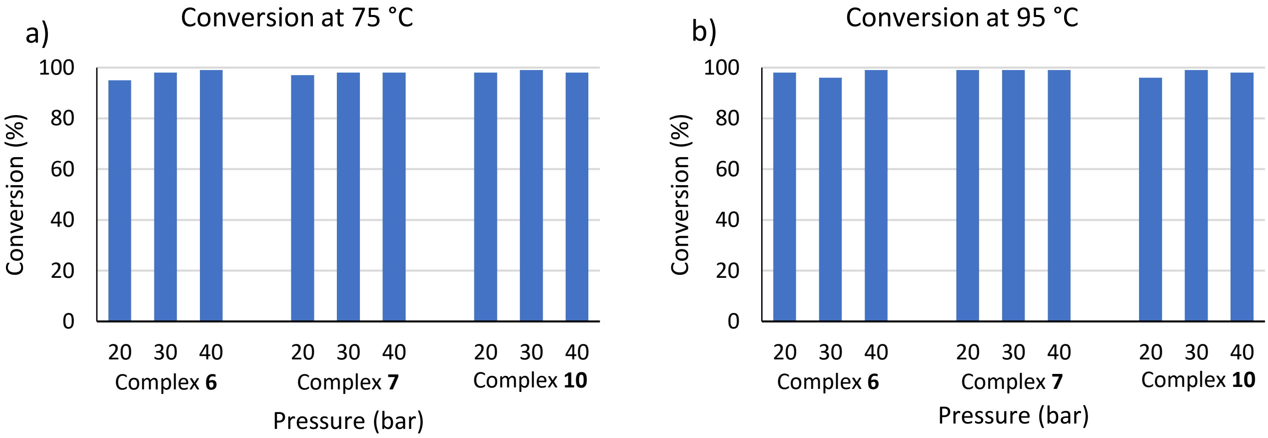


Figure 3.2: Conversion of 1-octene at (a) 75 and (b) 95 °C with the pressure varied.

Effect of temperature and pressure on chemoselectivity.

The chemoselectivity of complexes **6**, **7** and **10** was then studied at different temperatures (50, 75 and 95 °C) and pressures (20, 30 and 40 bar) while keeping all other reaction conditions constant.

At low pressure (20 and 30 bar), an increase in the iso-octenes is observed when temperature is increased, while an increase in temperature at 40 bar of syngas pressure led to a general increase in the formation of aldehydes (Figure 3.3). This can be attributed to the terminal octene being largely isomerised at high temperatures and, due to the low concentration of syngas in the system at low pressure, a great deal of the internal octenes are not hydroformylated. However, at 40 bar, a greater amount of the internal octenes is hydroformylated to give branched aldehydes. This further explains the increased selectivity for aldehydes observed at 40 bar (up to 93 % aldehydes with complex **6** at 75 °C, entry 8).

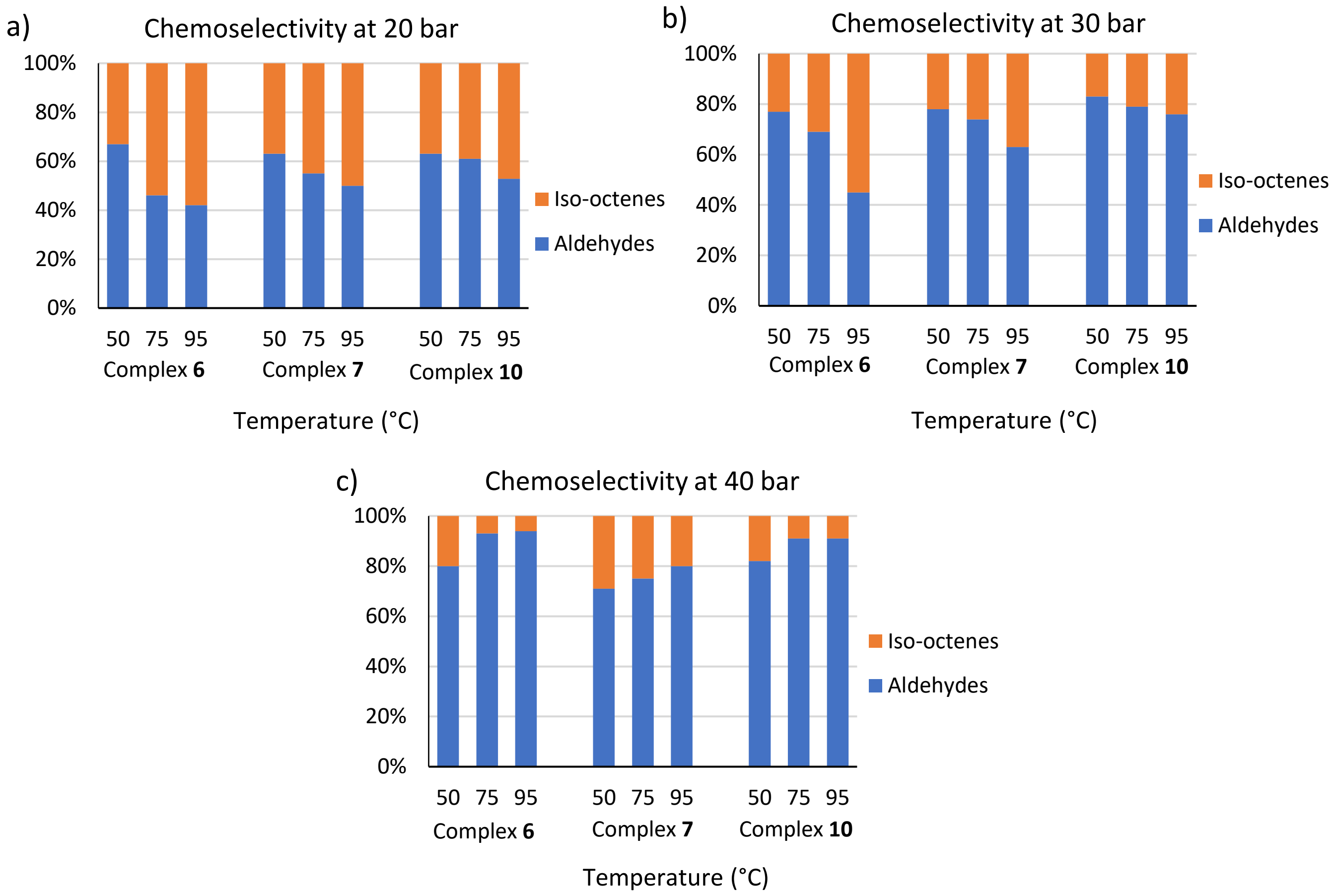


Figure 3.3: Chemoselectivity of complexes **6**, **7** and **10** while varying the temperature at (a) 20 bar, (b) 30 bar and (c) 40 bar.

Effect of temperature and pressure on regioselectivity.

The regioselectivity of the complexes was also studied at the different temperatures and pressures. Figure 3.4 shows the regioselectivity of the complexes at different pressure with changing temperature.

At 50 and 75 °C, all three complexes exhibit increased regioselectivity for linear aldehydes, with *n*:iso ratios as high as 2.6 for complex **6** at 75 °C and 20 bar (entry 2, Table 3.1). Branched aldehydes are favoured at 95 °C regardless of the pressure applied. This is again due to the increased production of iso-octenes at high temperature, which are then hydroformylated to give branched aldehydes. Thus, when using these complexes as pre-catalysts for the hydroformylation of 1-octene, the temperature should be selected according to the type of desired aldehyde (linear or branched).

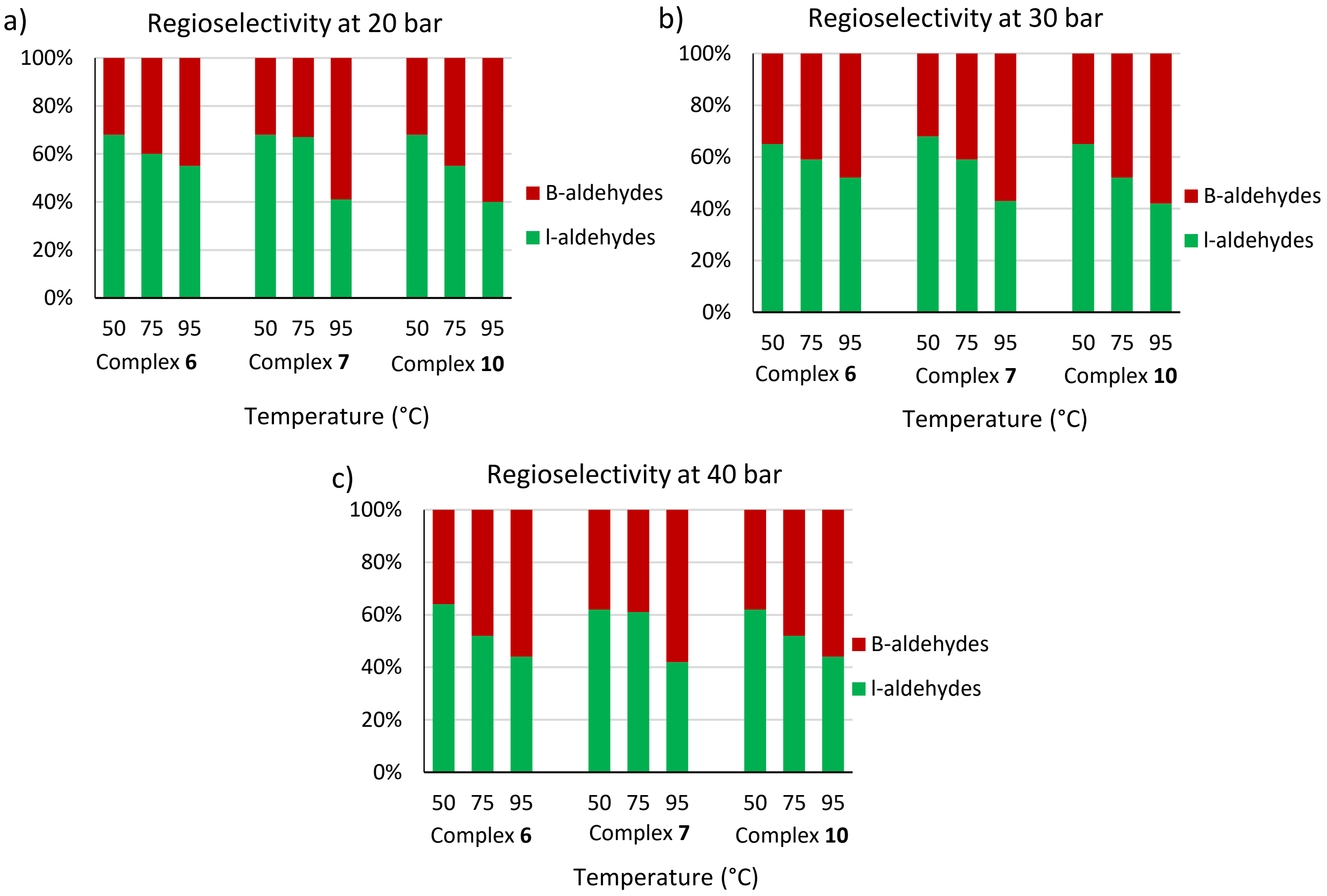


Figure 3.4: Regioselectivity of complexes **6**, **7** and **10** while varying the temperature at (a) 20 bar, (b) 30 bar and (c) 40 bar.

Increasing the pressure while keeping the temperature constant does not result in any significant improvement to the regioselectivity in the aqueous biphasic hydroformylation reactions with complexes **6**, **7** and **10** used as catalyst precursors (Figure 3.5). This implies that when using these complexes, the regioselectivity of the catalytic reaction is more dependent on the temperature than it is on the syngas pressure.

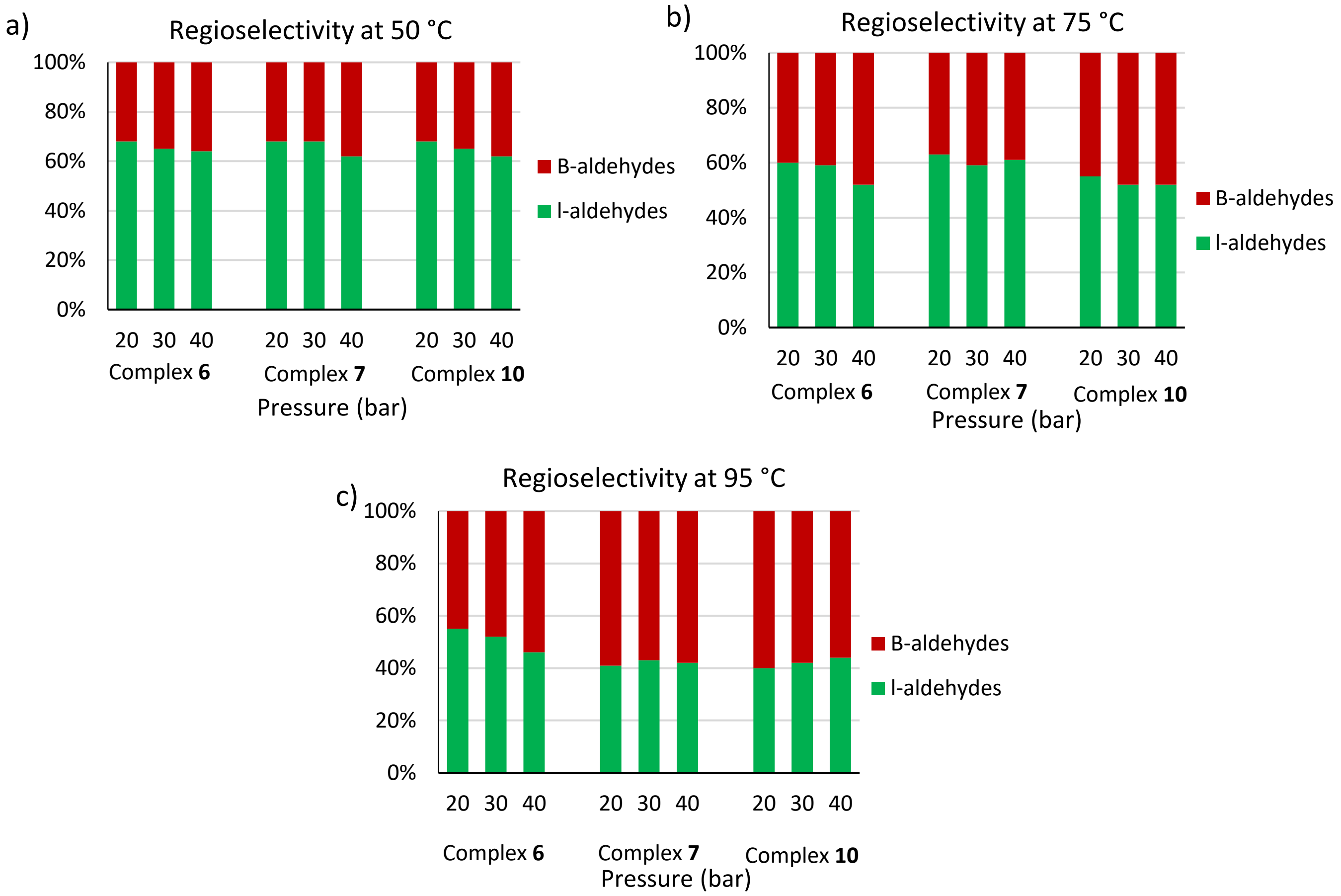


Figure 3.5: Regioselectivity of complexes **6**, **7** and **10** while varying the pressure at (a) 50 °C, (b) 75 °C and (c) 95 °C.

Effect of increasing metal centres.

When the trinuclear complex **10** is used, a significantly higher conversion of 1-octene is observed at 50 °C (up to 51 % at 40 bar, entry 25) when compared to the very poor conversion when using complexes **6** (17 %, entry 7) and **7** (26 %, entry 16) under the same conditions. This implies that the trinuclear complex **10** exhibits faster rates than the mononuclear (**6**) and dinuclear complexes (**7**). This observation is further studied and is discussed in section 3.2.3.

Optimal conditions.

At low temperature (50 °C) the catalyst precursors exhibit poor conversion of 1-octene. The optimal temperature for the catalyst precursors was established to be 75 °C, which favours linear aldehydes over branched aldehydes and the optimal pressure to be 40 bar, which in turn exhibits better chemoselectivity towards aldehydes. All three complexes exhibit good catalytic activity at these optimal conditions, with TOF values ranging between 200 and 300 h^{-1}. This is similar to the data previously reported by Smith and co-workers in the hydroformylation of 1-octene using water-soluble rhodium complexes.[5,31,34]

3.2.2 Aqueous biphasic hydroformylation of 1-octene at optimal conditions

All the complexes (**6** – **18**) were then studied as catalyst precursors in the aqueous biphasic hydroformylation of 1-octene at the optimal conditions (75 °C and 40 bar) for 8 hours. Table 3.2 shows results of these catalytic reactions.

Table 3.2: Hydroformylation results of 1-octene after 8 hours using complexes **1** – **10** as pre-catalysts.[i]

Entry	Complex	Conversion (%)	Aldehydes (%)			Iso-octenes (%)	*n*:iso	TOF (h^{-1})
			Total	linear	branched			
1	**6** (Rh-COD)	99±0.71	93±1.41	52±0.71	48±0.71	7±1.41	1.1±0.071	288±2.21
2	**7** (Rh-COD)	97±1.5	75±2.3	61±0.58	39±0.58	25±2.3	1.6±0.058	208±4.2
3	**8** (Rh-COD)	97±0.35	94±0.71	54±1.4	46±1.4	6±0.71	1.2±0.14	283±2.8
4	**9** (Rh-COD)	94±0.57	90±1.8	55±2.1	45±2.1	10±1.8	1.2±0.17	266±4.2
5	**10** (Rh-COD)	98±0.58	91±1.0	52±0.58	48±0.58	9±1.0	1.1±0.071	278±1.7
6	**11** (Rh-COD)	92±1.1	92±3.4	58±2.9	42±2.9	8±0.71	1.4±0.23	264±4.2
7	**12** (Rh-COD)	97±0.71	87±1.4	65±1.8	35±1.8	13±1.4	1.9±0.21	255±7.1
8	**13** (Rh-CO)	80±2.5	74±0.14	79±0.14	21±0.14	26±0.14	3.8±0.042	223±6.7
9	**14** (Rh-CO)	86±2.8	78±1.4	73±2.1	27±2.1	22±1.4	2.5±0.17	213±3.4
10	**15** (Rh-CO)	87±2.8	74±2.1	71±1.4	29±1.4	26±2.1	2.4±0.14	200±5.5
11	**16** (Rh-CO)	84±2.1	74±1.8	71±2.1	29±2.1	26±1.8	2.4±0.11	218±3.2
12	**17** (Rh-CO)	82±3.4	86±1.4	70±2.1	30±2.1	14±1.4	2.3±0.17	220±3.0
13	**18** (Rh-CO)	88±2.8	87±2.1	69±1.4	31±1.4	13±2.1	2.2±0.14	239±2.2

[i] Reactions carried out in toluene (5 mL) and distilled water (5 mL) with 7.18 mmol of 1-octene and 2.87 x 10^{-3} mmol of the Rh-PTA catalyst precursor varying the temperature and pressure of syngas ($CO:H_2$ = 1:1). GC conversions were obtained using *n*-decane as an internal standard in relation to authentic standard *iso*-octenes and aldehydes. TOF = (mol product/mol catalyst)h^{-1} and is based on total aldehydes.

All complexes exhibit very good to excellent conversion (greater than 80 %). The COD complexes (**6** – **12**) show greater conversion and are generally more active (with TOF values as high as 288 h^{-1}, entry 1) than complexes **13** – **18**, the carbonyl analogues. This could be attributed to the difference in electronic properties of the COD and CO ligands. The CO ligand is a strong π-acceptor whereas the COD ligand is a π-donor. Further studies would have to be conducted in order to determine the mechanism of the catalytic reactions followed when using catalyst precursors **6** – **18**. This would assist in further explaining the difference in conversion of 1-octene when using the COD complexes (**6** – **12**) and the CO complexes (**13** – **18**).

The chemoselectivity of the complexes at optimal conditions is displayed graphically in Figure 3.6. The COD complexes (**6** – **12**) display better chemoselectivity for aldehydes compared to the CO complexes (**13** – **18**). This is attributed to the COD complexes reaching near quantitative conversion after 8 hours, as a result, most of the iso-octenes that have formed are hydroformylated leading to a decrease in the amount of iso-octenes present and an increase in the amount of total aldehydes produced. No hydrogenation products (alkanes and alcohols) are observed for any of the catalyst precursors.

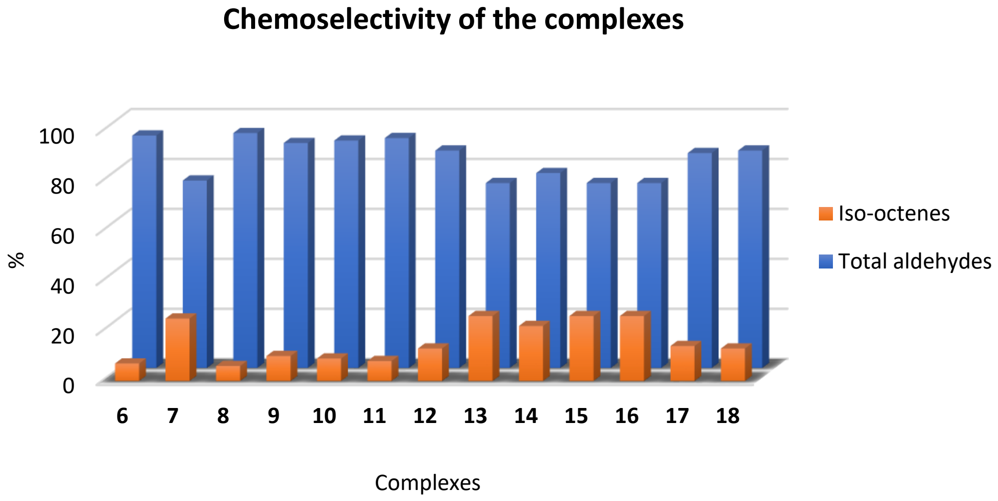


Figure 3.6: Chemoselectivity of the complexes studied for the aqueous biphasic hydroformylation of 1-octene.

The CO complexes (**13** – **18**) display better regioselectivity compared to the COD complexes (**6** – **12**) at optimal conditions (75 °C and 40 bar), as shown in Figure 3.7. The *n*:iso ratios of the COD complexes range between 1.1 and 1.9 whilst the *n*:iso ratios of the CO complexes go as high as 3.8±0.042 (entry 13). This is consistent with results obtained by Makhubela *et al*. when comparing regioselectivity exhibited by rhodium pre-catalysts that have COD and

CO as ligands.[15] This means that the carbonyl complexes are more selective for linear aldehydes than the COD complexes, a result that was not expected as the COD ligand is bulkier than the carbonyl ligand and thus complexes with COD ligands would be expected to exhibit increased selectivity towards linear aldehydes than the complexes with the CO ligands. This can again be explained by the observation that the COD complexes display higher conversion of 1-octene by 8 hours than the CO complexes. This then implies that a greater amount of the iso-octenes are hydroformylated when the COD complexes are used and thus giving an increased amount of branched aldehydes (i.e. low *n*:iso ratios) in comparison with the CO complexes.

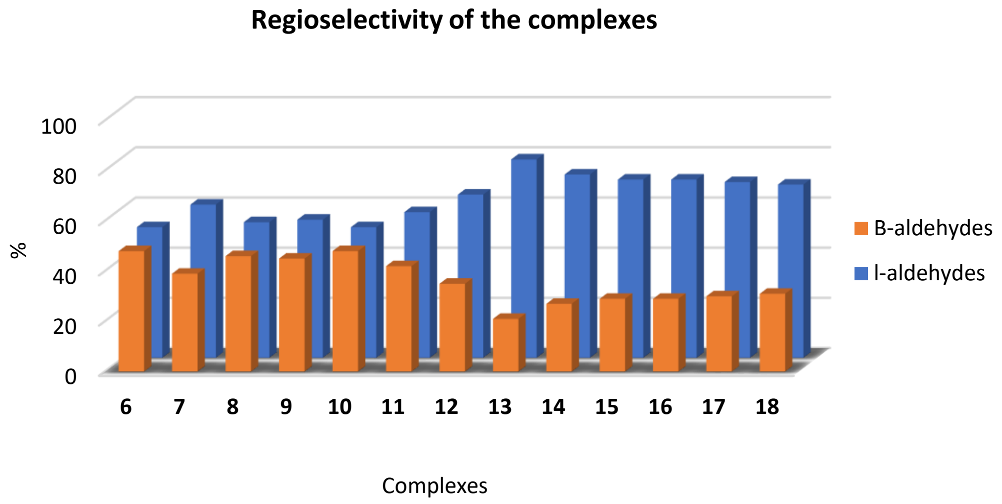
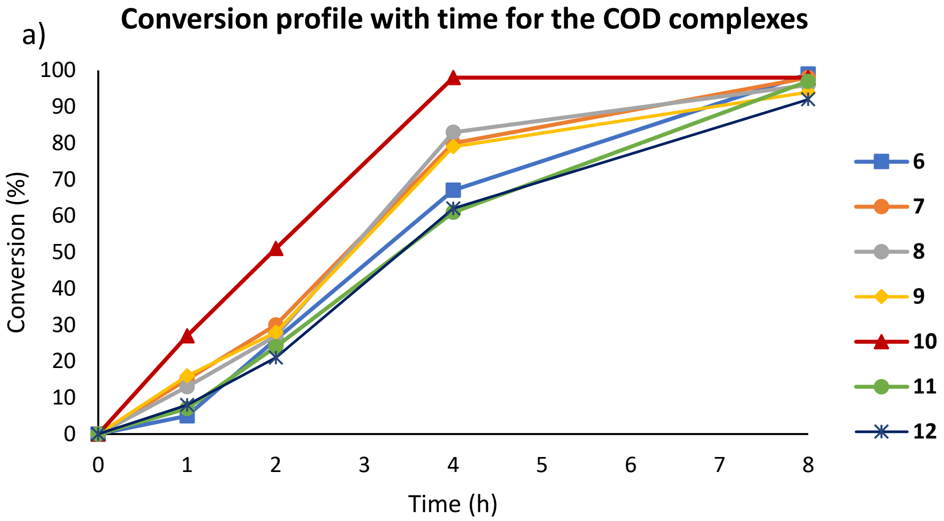


Figure 3.7: Regioselectivity of the complexes studied for the aqueous biphasic hydroformylation of 1-octene.

No significant difference in the activity and selectivity is observed at 8 hours with increasing the number of metal centres of the catalyst precursors nor is there a significant difference observed for the chelating complexes (**11**, **12**, **17** and **18**) and the non-chelating complexes (**7**, **8**, **14** and **15**) within either a series of the COD complexes or the CO complexes. This then motivated the study of the performance of each catalyst precursor at different time intervals, and the results of this study are discussed in Section 3.2.3.

3.2.3 Performance of catalyst precursors over time

The performance of each of catalyst precursor **6** – **18** was studied at different time intervals under the optimal catalytic conditions (75 °C and 40 bar). A sample was taken and analysed by GC after 1, 2, 4 and 8 hours for each catalyst precursor. Figure 3.8 illustrates the conversion profile of the catalyst precursors with time.


a) Conversion profile with time for the COD complexes

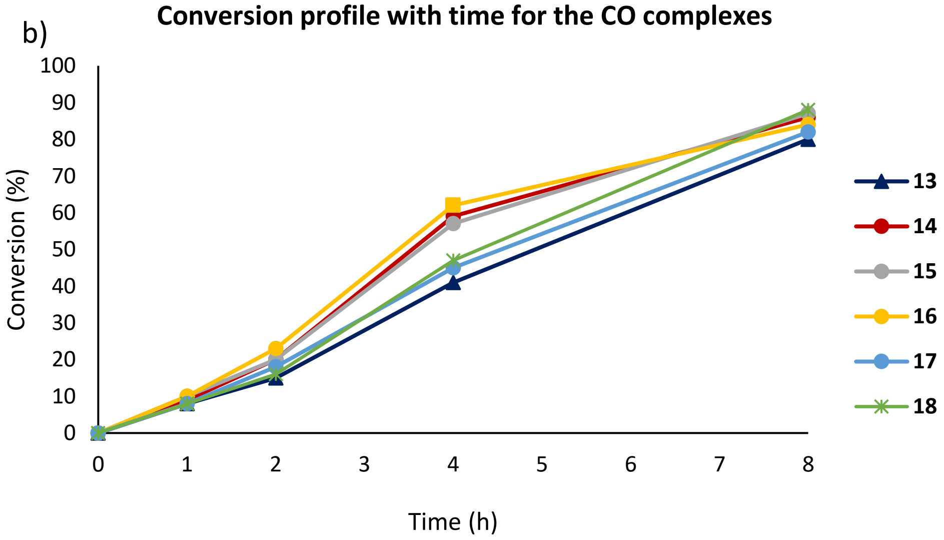

b) Conversion profile with time for the CO complexes

Figure 3.8: Conversion profile with time for the (a) COD and (b) CO complexes. Average error estimate: ±1.1 %.

The results show that at each time interval the trinuclear complex (**10**) exhibits higher conversion than all the other complexes, while the dinuclear complexes exhibit higher conversion than the mononuclear complexes in both COD and CO analogues. When using complex **10** as a catalyst precursor, maximum conversion is achieved after 4 hours. This infers that the trinuclear complex exhibits a faster rate than the dinuclear (**7** – **9** and **14** –**16**) complexes which, in turn, exhibit a faster rate than the mononuclear complexes (**6**, **11** – **13**, **17** and **18**) during the catalytic reactions. The results also suggest that the performance of the chelating complexes (**11**, **12**, **17** and **18**) is similar to those of the mononuclear complexes **6** and **13** as they exhibit similar trends in the conversion profile with time plots. Furthermore, the COD complexes (**6** – **12**) show accelerated conversion than the CO complexes (**13** – **18**) as at each time interval the COD complexes (Figure 3.8a) exhibit higher conversion than the CO complexes (Figure 3.8b).

The chemoselectivity and regioselectivity of the complexes (**6** – **18**) when used as catalyst precursors in the hydroformylation of 1-octene were also studied at different time intervals (1, 2, 4 and 8 hours). It was observed that the selectivity for aldehydes over iso-octenes improves with time for each complex (Figure 3.9). Consequently, the selectivity for linear aldehydes deteriorates with time while more branched aldehydes are observed (Figure 3.10). This could be explained by the fact that as the catalytic reaction proceeds, the iso-octenes produced are hydroformylated to give branched aldehydes and, thus, increasing the amount of total aldehydes present.

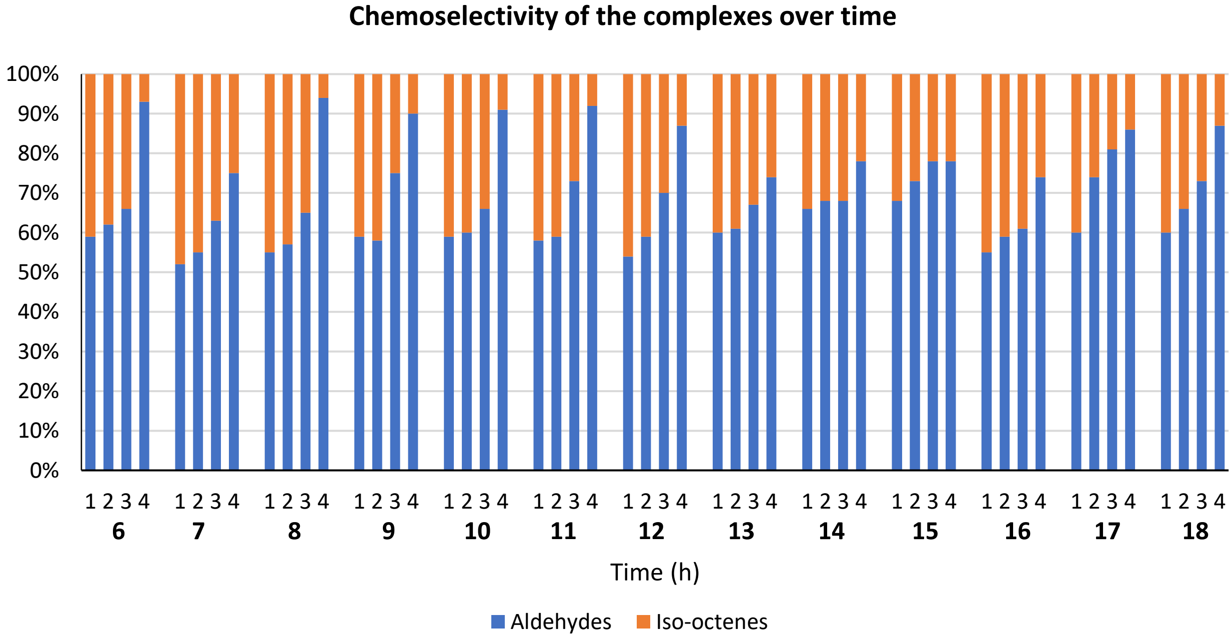


Figure 3.9: The chemoselectivity profile of the complexes over time. Average error estimate: ±2.1 %.

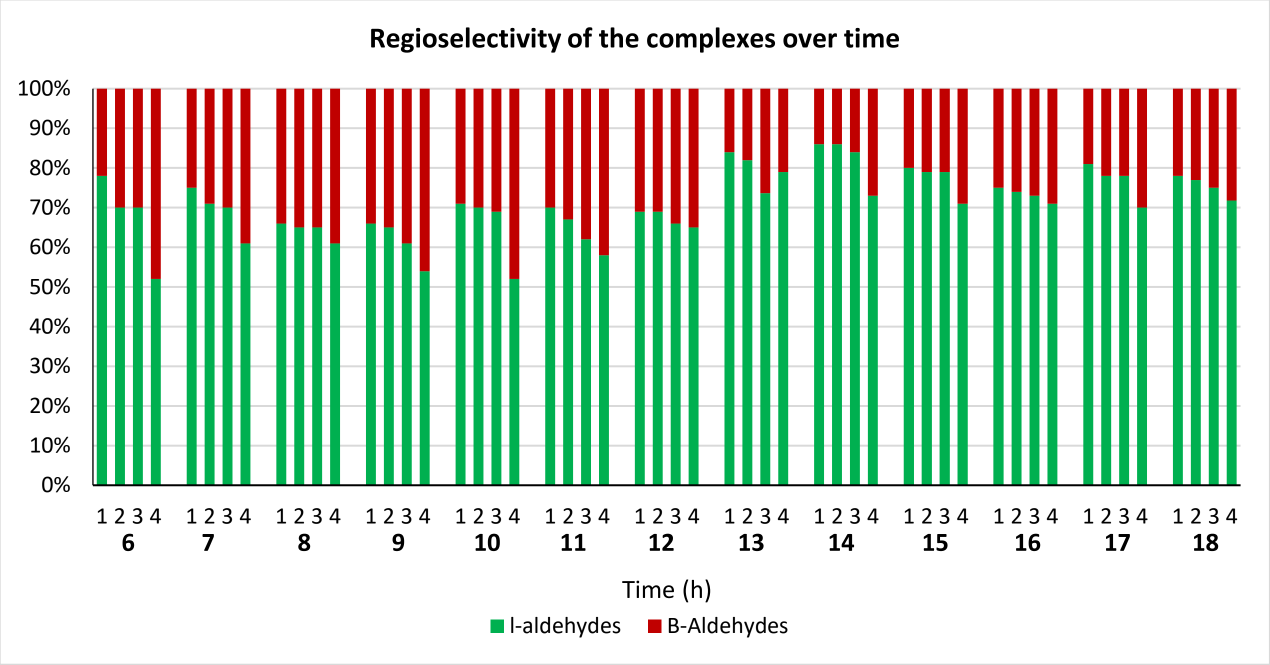


Figure 3.10: The regioselectivity profile of the complexes over time. Average error estimate: ±2.1 %.

The results of the chemoselectivity profile with time (Figure 3.9) shows that the amount of aldehydes is greater than the amount of iso-octenes produced at each time interval for each complex. This suggests that all the complexes predominantly behave as hydroformylation catalysts as opposed to isomerisation catalysts. This is further corroborated by the regioselectivity profile of the complexes over time (Figure 3.10). There is generally a high percentage of linear aldehydes produced at 1 hour for each complex (up to 86 % for complex **14**), and all complexes exhibit selectivity for linear aldehydes throughout the duration of the catalytic reaction. Since linear aldehydes are obtained from direct hydroformylation of the substrate *via* anti-Markovnikov insertion,[4,35] the regioselectivity profile indicates that each complex behaves largely as hydroformylation catalysts.

3.2.4 Recyclability and leaching studies

Recyclability studies were performed by cooling the reaction mixture to 0 °C and the toluene layer decanted. A fresh sample of 1-octene and *n*-decane dissolved in toluene was then added onto the aqueous layer and the hydroformylation reaction repeated. The results of the recyclability studies are shown in Figure 3.11. The catalysts could be recycled three times with the conversion of 1-octene decreasing drastically after each run for each catalyst precursor. The conversion had decreased to below 25 % by the third run. This decrease in conversion could be attributed to the low concentration of the catalyst precursors in the aqueous layer as a result of the catalyst precursors leaching into the organic layer.

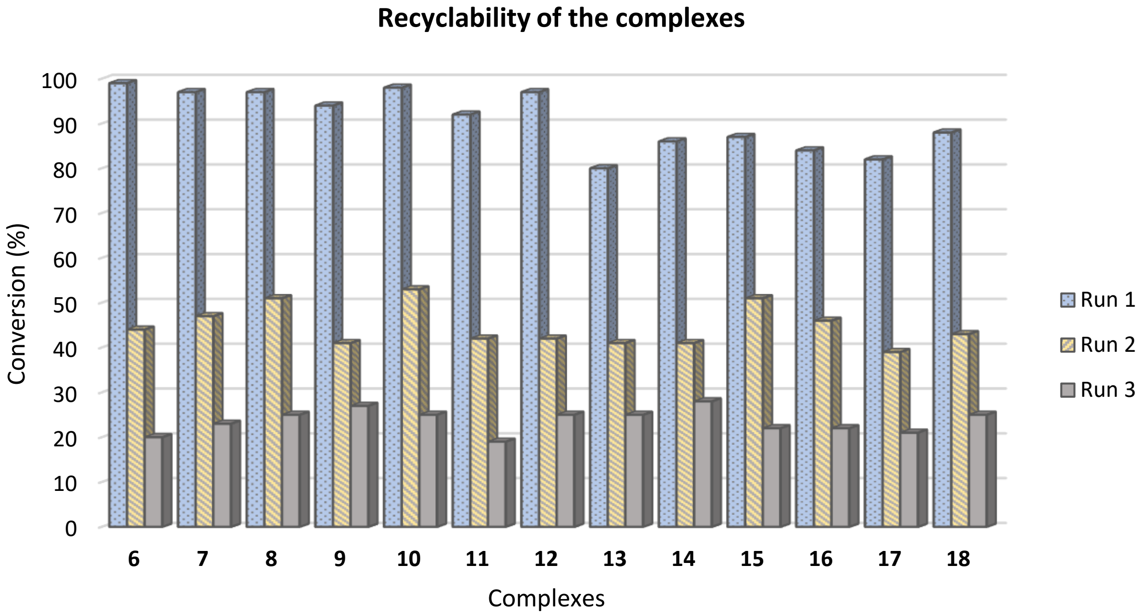


Figure 3.11: Recyclability studies of the complexes at optimal conditions. Average error estimate: ±1.8 %.

After each catalytic run, the organic layer (which was initially clear) was yellow (Figure 3.12), implying loss of the catalyst precursor from the aqueous layer into the organic layer. Inductively coupled plasma optical emission spectrometry (ICP-OES) was used to quantify the loss of the catalyst precursors **6** – **18** into the organic layer by analysing the aqueous and organic layers of each catalyst precursor before and after the hydroformylation reaction. The results show that more than 90 % of each catalyst precursor leaches into the organic layer after the first run. These results corroborate the notion of leaching of the catalyst precursors which then led to the observed significant drop in the conversion after the first run (Figure 3.11). The huge loss of the complexes into the organic layer could be due to the catalyst precursors being soluble in toluene at elevated temperatures and pressures.

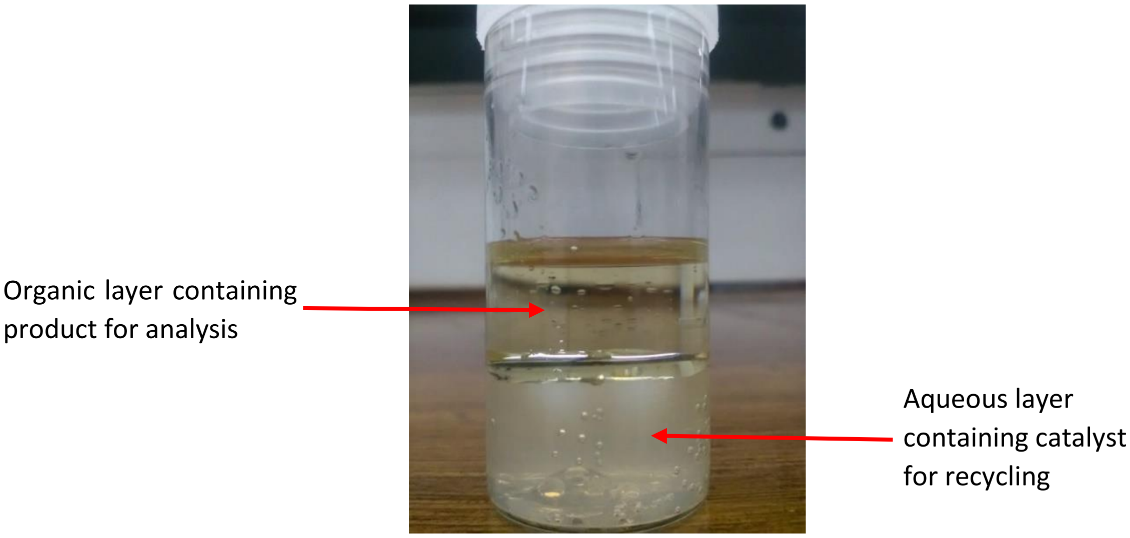


Figure 3.12: Biphasic catalytic system of complex **6** after the first catalytic run.

3.2.5 Mercury poisoning studies

Mercury poisoning study is important as it suppresses unwanted heterogeneous catalysts (nanoparticles) and thus determines whether the catalyst precursors are entirely homogeneous under the catalytic conditions. Free metal particles can be responsible for heterogeneous catalysis which therefore does not a true reflection of the performance of the catalyst precursors as homogeneous catalysts. Mercury(0) is added to the catalytic reactions which can form amalgams with any free metal particles present, thus inhibiting the activity of the heterogeneous catalysts which may also exist as nanoparticles.

A drop of mercury was added to the reactor at the beginning of the hydroformylation reaction (t = 0 hours) and the catalytic reaction conducted under optimal conditions (75 °C and 40 bar) for 8 hours using each one of catalyst precursors **6** – **18**. The layers were then separated and the organic layer analysed using GC. Figure 3.13 shows the results obtained from these experiments. The conversion of 1-octene in the presence of mercury agrees (within experimental uncertainty) with the conversion of 1-octene obtained without mercury for all complexes employed. This suggests that only the molecular species is responsible for the conversions observed and not nanoparticles, thus all complexes (**6** – **18**) behave entirely as homogeneous catalysts under the catalytic conditions.

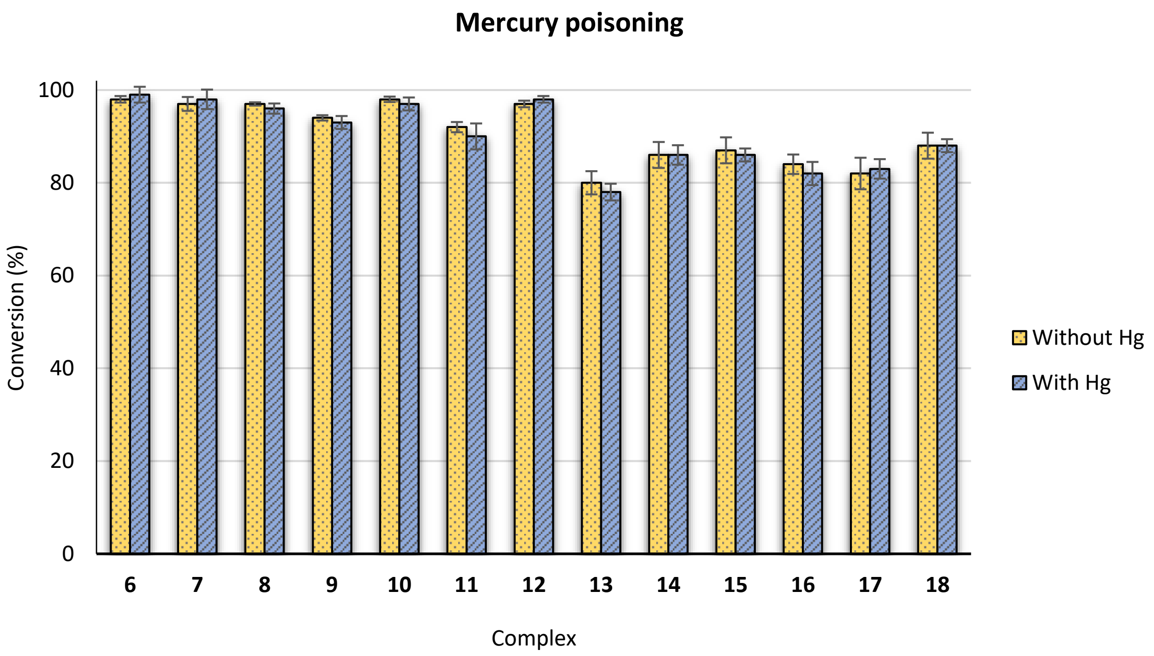


Figure 3.13: Comparison of 1-octene conversion in the absence and presence of mercury. Average error estimate ±1.6 %.

3.3 Summary

A series of mono-, di- and trinuclear water-soluble Rh(I)-PTA complexes were evaluated as catalyst precursors for the hydroformylation of 1-octene. All complexes were active in the hydroformylation of 1-octene to aldehydes, with TOF values over 200 h^{-1}. The COD complexes (**6** – **12**) proved to be more active than the CO complexes (**13** – **18**). Moreover, the COD complexes exhibit better chemoselectivity for aldehydes whilst the CO complexes exhibit better regioselectivity for linear aldehydes. This is due to the CO complexes not reaching quantitative conversion at 8 hours whereas all COD complexes reach quantitative conversion under the catalytic conditions. Increasing the number of metal centres had no significant effect on the chemo- and regioselectivity at 8 hours, but studies of the catalyst precursors over time showed that increasing the number of metal centres increased the rate of the catalytic reaction. This is demonstrated by the trinuclear complex displaying a faster catalytic rate than the dinuclear complexes which, in turn, display faster rates than the mononuclear complexes. Mercury poisoning experiments confirmed that all the catalysts precursors behave entirely as homogeneous catalysts when used for the aqueous biphasic hydroformylation of 1-octene. The complexes exhibited poor recyclability, attributed to significant leaching of the complexes into the toluene layer. ICP-OES studies showed that *ca.* 90 % of each complex leaches into the toluene layer after the first run. The leaching could be as a result of the complexes being soluble in toluene under the catalytic conditions.

3.4 References

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Chapter 4

Experimental

4.1 General details

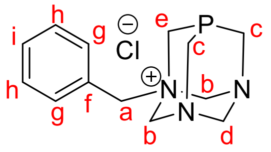
All reactions were carried out in an atmosphere of nitrogen unless otherwise stated. Solvents were reagent grade and were dried and degassed prior to use. All chemicals were purchased from Sigma Aldrich and used as received. $RhCl_3 \cdot 3H_2O$ was purchased from Heraeus South Africa and used as received.

^1H NMR spectra were recorded on a Brucker 300 MHz and $^{13}C\{^1H\}$ and $^{31}P\{^1H\}$ were recorded on a Brucker Ultrashield 400 MHz ($^{13}C\{^1H\}$: 101 MHz, ^{31}P: 162 MHz) spectrometer. Chemical shifts were reported in parts per million (ppm) relative to the internal standard tetramethylsilane (δ 0.00, for ^1H and $^{13}C\{^1H\}$ NMR) and phosphoric acid (δ 0.00, for $^{31}P\{^1H\}$ NMR). Melting points were obtained using a BÜCHI melting point apparatus B-540. Mass spectrometry was performed using a Waters Synapt G2 electron spray ionisation mass spectrometer in the positive or negative-ion mode and elemental analyses was performed on a Thermos Scientific FLASH 2000 CHNS-O Analyzer at the University of Johannesburg. FT-IR spectra were recorded using Attenuated Total Reflectance Infrared spectroscopy (ATR-IR) and LC–MS data was recorded using an Agilent LC–MS system.

Catalytic products were analysed and quantified using a Varian CP-8400 GC instrument and ICP-OES Varian 750-ES spectrophotometer was used to conduct inductively coupled plasma optical emission spectrometry experiments.

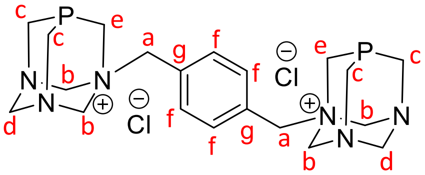
4.2 Synthesis and characterisation of the alkylated PTA ligands

*4.2.1 Synthesis of the monomeric ligand (**1**)*[1]



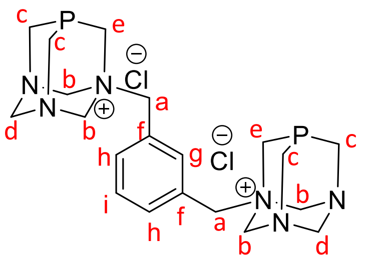
The monomeric ligand **1** was prepared according to previously reported literature procedures.[1] Benzyl chloride (0.0950 mL, 0.830 mmol) was added to a stirring solution of PTA (131 mg, 0.834 mmol) in methanol (5 mL). The reaction mixture was refluxed for 2 hours, after which the volume of the solvent was reduced to *ca*. 2 mL under reduced pressure. Diethyl ether was then added to afford ligand **1** as a white precipitate which was isolated using suction filtration and washed with methanol. Ligand **1** was then recrystallized from methanol and diethyl ether and dried under vacuum. **Yield**: 173 mg, 73 %. **M.p.**: 116.2 – 119.8 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.55 (br s, 5H, ArH), 5.14 – 4.88 (AB q, ^2J = 11.1 Hz, 4H, H_b), 4.52 – 4.38 (AB q, ^2J = 15.5, 8.8 Hz, 2H, H_d), 4.28 (d, ^2J = 6.1 Hz, 2H, H_e), 4.18 (s, 2H, H_a), 3.94 – 3.76 (m, 4H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 132.68 (C_i), 129.91 (C_g), 128.56 (C_h), 125.49 (C_f), 78.36 (C_b), 68.78 (C_d), 64.33 (C_a), 51.30 (C_e), 45.16 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -82.35. **ESI-MS(-)**: *m/z* 194.1128 $[M–Bn]^-$. **Elemental Analysis** for $C_{13}H_{19}ClN_3P$: Calcd. C 55.03, H 6.75, N 14.81 %. Found C 54.62, H 6.53, N 14.81 %. **$S_{20 °C}$** = 200 mg/mL in H_2O.

*4.2.2 Synthesis of the 1,4-dimeric ligand (**2**)*[2]



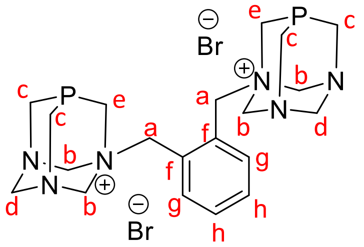
Ligand **2** was prepared by reacting 1,4-bis(chloromethyl)benzene (111 mg, 0.634 mmol) with two equivalents of PTA (201 mg, 1.28 mmol) in acetone (45 mL) as reported in literature with minor modifications.[2] The reaction mixture was refluxed for 2 hours. This afforded ligand **2** as a white precipitate which was then isolated by suction filtration, washed with cold acetone and dried under vacuum. **Yield:** 233 mg, 75 %. **M.p.**: 152.9 – 154.2°C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.77 (s, 4H, ArH), 5.18 – 4.97 (m, 8H, H_b), 4.70 – 4.51 (dd, 4H, H_d), 4.34 (d, ^2J = 8.5 Hz, 4H, H_e), 4.27 (s, 4H, H_a), 4.11 – 3.84 (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 133.72 (C_f), 127.40 (C_g), 79.11 (C_b), 69.38 (C_d), 66.09 (C_a), 53.08 (C_e), 45.56 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -82.42. **ESI-MS(+):** *m/z* 207.0254 $[M–2Cl]^{2+}$. **Elemental analysis:** $C_{20}H_{32}Cl_2N_6P_2$: Calcd. C 49.09, H 6.59, N 17.17 %. Found C 48.99, H 6.55, N 16.42 %. **$S_{20°C}$** = 200 mg/mL in H_2O.

*4.2.3 Synthesis of the 1,3-dimeric ligand (**3**)*[2]



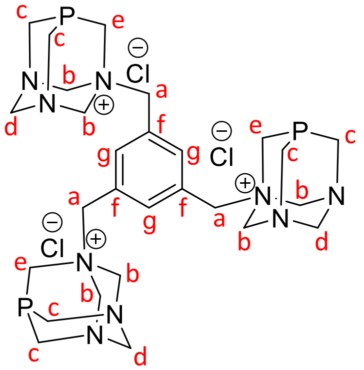
Ligand **3** was prepared according to previously reported literature procedures with minor modifications.[2] 1,3-Bis(chloromethyl)benzene (111 mg, 0.636 mmol) was added to a boiling solution of PTA (201 mg, 1.28 mmol) in acetone (45 mL). The reaction mixture was refluxed for 2 hours then cooled to room temperature giving ligand **3** as a white precipitate which was isolated using suction filtration, washed with cold acetone and dried under vaccum. **Yield**: 302 mg, 97 %. **M.p.**: 191.2 – 195.3 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.85 – 7.51 (m, 4H, ArH), 5.18 – 4.94 (m, 8H, H_b), 4.62 (dd,4H, H_d), 4.35 (d, 4H, H_e), 4.27 (s, 4H, H_a), 4.03 – 3.85 (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 133.03 (C_g), 131.21 (C_i), 130.10 (C_h), 125.32 (C_f), 79.02 (C_b), 69.52 (C_d), 66.54 (C_a), 53.05 (C_e), 45.67 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -82.40. **ESI-MS(+)**: *m/z* 206.9804 $[M–2Cl]^{2+}$. **Elemental Analysis**: $C_{20}H_{32}Cl_2N_6P_2$: Calcd. C 49.09, H 6.59, N 17.17 %. Found C 49.03, H 6.78, N 16.67 %. **$S_{20°C}$** = 600 mg/mL in H_2O.

*4.2.4 Synthesis of the 1,2 dimeric ligand(**4**)*[2]



Ligand **4** was synthesised by following previously reported literature procedures.[2] PTA (200. mg 1.27 mmol) was dissolved in acetone (45 mL) at 60 °C. 1,2-bis(bromomethyl)benzene (171 mg 0.648 mmol) was then added. The reaction mixture was stirred under reflux at for 2 hours. Ligand **4** was obtained as a white powder which was isolated by suction filtration, washed with dichloromethane and recrystallised from methanol and diethyl ether. **Yield:** 311 mg, 84 %. **M.p.:** 203.4 – 207.3 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.82 – 7.69 (m, 4H, ArH), 5.40 (d, ^2J = 11.0 Hz, 4H, H_b), 5.16 (d, ^2J = 10.7 Hz, 4H, H_b), 4.61 – 4.38 (m, 12H, $H_{a,e,d}$), 3.98 – 3.69 (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 135.48 (C_g), 130.65 (C_h), 127.54 (C_f), 78.26 (C_b), 69.03 (C_d), 60.85 (C_a), 50.82 (C_e), 45.28 (C_c). **^{31}P{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): -82.07. **ESI-MS(+)**: *m/z* 207.0037 $[M{-}2Br]^{2+}$. $C_{20}H_{32}N_6Br_2P_2{\cdot}4H_2O$: Calcd. C 36.94, H 6.20, N 12.92 %. Found C 37.22, H 6.11, N 12.73 %. **$S_{20°C}$** = 1000 mg/mL in H_2O.

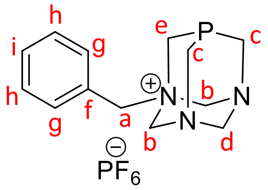
4.2.5 *Synthesis of the trimeric ligand (**5**)*[3]



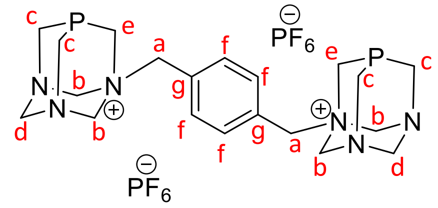
Ligand **5** was synthesised by following previously reported literature procedures.[3] PTA (259 mg 1.65 mmol) was added to a stirring solution of 1,3,5-tris(chloromethyl)benzene (92.5 mg 0.412 mmol) in acetone (10 mL). The reaction mixture was refluxed overnight and ligand **5** was obtained as a beige solid which was isolated by suction filtration, washed with dichloromethane and chloroform and dried under vacuum. **Yield**: 278 mg, 97 %. **M.p.**: Decomposes without melting, onset at 182.6 °C (lit. decomposes at 180.2 °C). **^{1}H NMR** (DMSO–d_6, δ ppm): 7.99 (s, 3H, ArH), 5.26 – 5.07 (m, 12H, H_b), 4.66 – 4.54 (m, 6H, H_d), 4.50 (d, ^2J = 5.9 Hz, 6H, H_e), 4.40 (s, 6H, H_a), 4.12 – 3.84 (m, 12H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 139.44 (C_g), 127.90 (C_f), 79.22 (C_b), 69.39 (C_d), 65.31 (C_a), 52.98 (C_e), 45.44 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -82.07. **LC–MS(*m/z*)**: 390.9 $[M–Cl+H]^{2+}$. **Elemental Analysis** for $C_{27}H_{45}N_9Cl_3P_3{\cdot}5H_2O$: Calcd. C 41.31, H 7.06, N 16.06 %. Found C 41.51, H 6.74, N 15.18 %. **$S_{20°C}$** = 400 mg/mL in H_2O.

4.2.6 *General procedure for the synthesis of ligands **1'** – **5'***

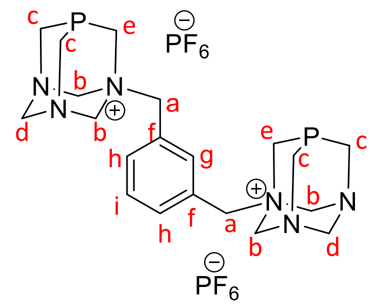
Either one of ligands **1** (101 mg, 0.356 mmol), **2** (199 mg, 0.407 mmol), **3** (200. mg, 0.409 mmol), **4** (200. mg, 0.409 mmol) or **5** (200. mg, 0.288 mmol) was dissolved in ethanol (50 mL). Appropriate equivalents of ammonium hexafluorophosphate (69.2 mg, 0.425 mmol for ligand **1'**; 140. mg, 0.859 mmol for ligands **2'**, **3'** and **4'** and 150. mg, 0.920 mmol for ligand **5'**) were added and the reaction mixture stirred at room temperature for 72 hours. The ligands precipitated out of solution as white solids which were isolated by suction filtration and dried under vacuum.



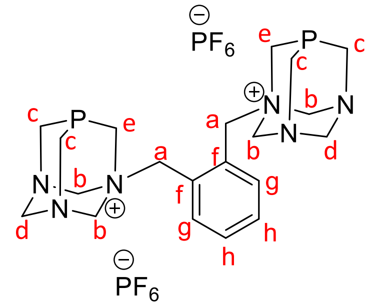
Ligand 1': Yield: 231 mg, 83 %. **M.p.:** 145.4 – 146.6 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.67 – 7.44 (m, ^3J = 4.0 Hz, 5H, ArH), 5.04 – 4.82 (AB q, ^2J = 11.0 Hz, 4H, H_b), 4.47 – 4.33 (AB q, ^2J = 13.2 Hz, 2H, H_d), 4.22 (d, ^2J = 5.4 Hz, 2H, H_e), 4.07 (s, 2H, H_a), 3.93 – 3.76 (m, ^2J = 11.4 Hz, 4H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 133.38 (C_g), 130.71 (C_i), 129.52 (C_h), 126.24 (C_f), 79.31 (C_b), 69.87 (C_d), 65.42 (C_a), 52.17 (C_e), 45.92 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -83.50 (s, PTA), -144.18 (sept, ^1J = 711.3 Hz, PF_6). **ESI-MS(+)**: *m/z* 248.1320 $[M–PF_6]^+$. **Elemental Analysis**: $C_{13}H_{19}F_6N_3P_2$: Calcd. C 39.70, H 4.87, N 10.69 %. Found C 38.84, H 4.47, N 10.66 %. **$S_{20°C}$** = 4 mg/mL in H_2O.



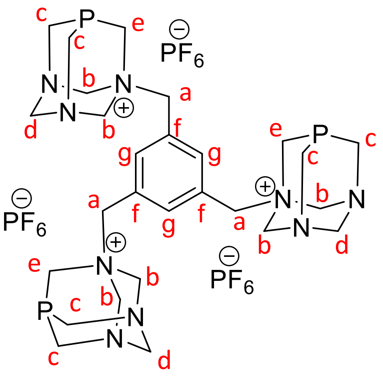
Ligand 2': Yield: 262 mg, 91 %. **M.p.**: 182.4 – 185.4 °C **^{1}H NMR** (DMSO–d_6, δ ppm): δ 7.61 (s, 4H, ArH), 5.06 – 4.85 (AB q, 8H, H_b), 4.59 – 4.33 (AB q, 4H, H_d), 4.24 (d, *J* = 4.4 Hz, 4H, H_e), 4.14 (s, 4H, H_a), 3.91 – 3.80 ppm (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 133.93 (C_f), 128.17 (C_g), 79.44 (s, C_b), 69.85 (s, C_d), 64.63 (s, C_a), 52.35 (d, C_e), 45.88 (d, C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -83.63 (s, PTA), -144.17 (sept, ^1J = 711.2 Hz, PF_6). **ESI-MS(+)**: *m/z* 209.1084 $[M–2PF_6]^{2+}$. **Elemental Analysis**: $C_{20}H_{32}F_{12}N_6P_4$: Calcd. C 33.91, H 4.55, N 11.86 %. Found C 34.02, H 5.16, N 11.12 %. **$S_{20°C}$** = 5 mg/mL in H_2O.



Ligand 3′: Yield: 285 mg, 94 %. **M.p.:** 192.7 – 196.1 °C. **^{1}H NMR** (DMSO–*d$_6$*, *δ* ppm): 7.69 – 7.46 (m, 4H, ArH), 5.04 – 4.82 (AB q, 8H, H$_b$), 4.57 – 4.32 (AB q, ^2J = 13.2 Hz, 4H, H$_d$), 4.22 (d, ^2J = 6.1 Hz, 4H, H$_e$), 4.09 (s, 4H, H$_a$), 3.93 – 3.76 (m, 8H, H$_c$). **^{13}C{^{1}H} NMR** (DMSO–*d$_6$*, *δ* ppm): 133.46 (C$_g$), 131.02 (C$_i$), 130.07 (C$_h$), 126.88 (C$_f$), 79.34 (C$_b$), 69.85 (C$_d$), 64.94 (C$_a$), 52.18 (C$_e$), 45.92 (C$_c$). **^{31}P{^{1}H} NMR** (DMSO–*d$_6$*, *δ* ppm): -83.67 (s, PTA), -144.18 (sept., ^1J = 711.2 Hz, PF$_6$) ppm. **LC-MS(*m/z*)**: 148.9 [M–2PF$_6$+Na]$^{3+}$. **Elemental Analysis**: $C_{20}H_{32}F_{12}N_6P_4$: Calcd. C 33.91, H 4.55, N 11.86 %. Found C 33.30, H 5.01, N 11.11 %. **S$_{20°C}$** = 5 mg/mL in H$_2$O.



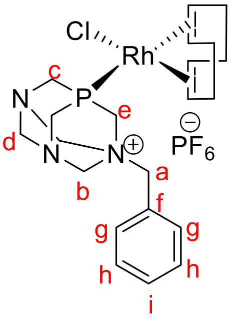
Ligand 4′: Yield: 91.9 mg, 76 %. **M.p.:** 150.3 – 152.7 °C. **^{1}H NMR** (DMSO–*d$_6$*, *δ* ppm): 7.66 (s, 4H, ArH), 5.14 – 4.94 (AB q, 8H, H$_b$), 4.60 – 4.49 (m, 4H, H$_d$), 4.33 (br s, ^2J = 4.4 Hz, 4H, H$_e$), 4.21 (s, 4H, H$_a$), 3.93 – 3.78 (m, 8H, H$_c$). **^{13}C{^{1}H} NMR** (DMSO–*d$_6$*, *δ* ppm): 135.85 (C$_g$), 131.36 (C$_h$), 127.74 (C$_f$) 79.42 (C$_b$), 69.75 (C$_d$), 61.98 (C$_a$), 51.84 (C$_e$), 45.85 (C$_c$). **^{31}P{^{1}H} NMR** (DMSO–*d$_6$*, *δ* ppm): -82.38 (s, PTA), -144.35 (sept, ^1J = 711.3 Hz, PF$_6$). **LC-MS(*m/z*)**: 149.0 [M–2PF$_6$+Na]$^{3+}$. **Elemental Analysis**: $C_{20}H_{32}F_{12}N_6P_4$: Calcd. C 33.91, H 4.55, N 11.86 %. Found C 33.42, H 5.08, N 11.02 %. **S$_{20°C}$** = 5 mg/mL in H$_2$O.



Ligand 5’: Yield: 243 mg, 82 %. **M.p.:** 322.9 – 326.1 °C. **^{1}H NMR** (DMSO–*d$_6$*, *δ* ppm): 77.5 (s, 3H, ArH), 5.27 – 5.09 (AB q, ^2J = 11.0 Hz, 12H, H_b), 4.64 (d, ^2J = 4.8 Hz, 6H, H_e), 4.50 – 4.11 (m, ^2J = 16.5 Hz, 6H, H_d), 4.06 (s, 6H, H_a), 4.04 – 3.84 (m, 12H, H_c). **^{13}C{^{1}H} NMR** (DMSO–*d$_6$*, *δ* ppm): 139.16 (C_g), 128.23 (C_f), 78.85 (C_b), 69.71 (C_d), 64.47 (C_a), 51.78 (C_e), 45.58 (C_c). **^{31}P{^{1}H} NMR** (DMSO–*d$_6$*, *δ* ppm): -82.63 (s, PTA), -144.18 (sept., ^1J = 711.2 Hz, PF_6). **ESI-MS(+)**: *m/z* 366.6320 $[M{-}2PF_6]^{2+}$. **Elemental Analysis**: $C_{27}H_{45}F_{18}N_9P_6$: Calcd. C 31.68, H 4.43, N 12.32 %. Found C 32.09, H 5.38, N 11.72 %. **$S_{20°C}$** = 4 mg/mL in H_2O.

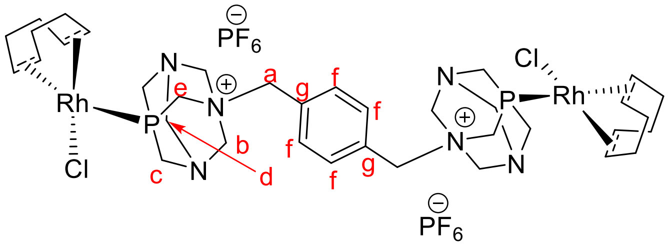
4.3 Synthesis and characterisation of mono-, di- and trinuclear Rh-PTA complexes

*4.3.1 Synthesis of the mononuclear complex (**6**)[4]*



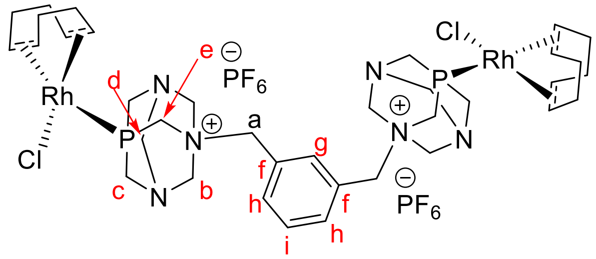
The synthetic method reported by Hapiot and Gonsalvi[4] was followed (with minor modifications) in the synthesis of complex **6**. $[RhCl(COD)]_2$ (63.5 mg, 0.129 mmol) was dissolved in DCM (50 mL). Ligand **1’** (100. mg, 0.254 mmol) was then added and the reaction mixture stirred at room temperature for 1.5 hours, after which the solution was concentrated to *ca.* 10 mL. Cold dried pentane was then added affording complex **6** as a yellow precipitate which was then isolated by suction filtration and dried under vacuum. **Yield:** 159 mg, 98 %. **M.p.:** Decomposes without melting, onset at 164.9 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.57 - 7.50 (m, 4H, ArH), 5.07 – 4.87 (AB q, ^2J = 10.5 Hz, 4H, H_b), 4.77 (d, ^2J = 10.8 Hz, 1H, H_d), 4.51 – 4.47 (m, 5H, H_{cod}, H_d), 4.33 (d, 2H, H_e), 4.22 (s, 2H, H_a), 4.12 – 3.94 (m, 4H, H_c), 2.45 – 2.19 (m, 4H, H_{cod}), 2.02 – 2.00 (m, ^3J = 8.1 Hz, 4H, H_{cod}). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 133.39 (C_g), 130.83 (C_i), 129.85 (C_h), 128.88 (C_f), 126.12 (C_{cod}), 78.75 (C_b), 64.35 (C_d), 68.09 (C_a), 55.35 (C_e), 52.12 (C_c), 27.98 (C_{cod}). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -32.67 (d, $^1J_{Rh-P}$ = 136.0 Hz, PTA), -144.18 (sept., ^1J = 711.2 Hz, PF_6). **ESI-MS(+)**: *m/z* 264.1263 $[M–PF_6+Na]^{2+}$. **Elemental Analysis**: $C_{36}H_{56}Cl_2F_{12}N_6P_4Rh_2$: Calcd. C 39.42, H 4.88, N 6.57 %. Found C 38.72, H 5.17, N 5.61 %. **$S_{40°C}$** = 3 mg/mL in H_2O.

*4.3.2 Synthesis of the 1,4-dinuclear complex (**7**)*



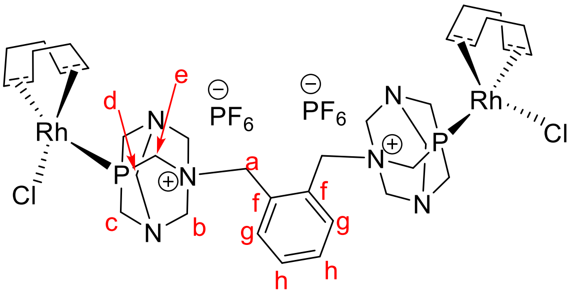
$[RhCl(COD)]_2$ (70.4 mg, 0.143 mmol) was dissolved in DCM (40 mL) and ligand **2'** (100. mg, 0.141 mmol) was then added. The reaction mixture was stirred at room temperature with ligand **2'** in suspension for 2 hours. Complex **7** was observed as a yellow solid precipitating out of solution. The complex was then isolated by suction filtration, washed with copious amounts of methanol to get rid of unreacted ligand **2'** and then dried under vacuum. **Yield:** 159 mg, 94%. **M.p.:** Decomposes without melting, onset at 286.2 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.67 (s, 4H, ArH), 5.09 – 5.05 (m, ^2J = 12.1 Hz, 8H, H_b), 4.91 – 4.75 (AB q, 4H, H_d), 4.54 – 4.50 (m, 8H, H_{cod}), 4.36 (d, 4H, H_e), 4.30 (s, 4H, H_a), 4.13 – 4.08 (m, 8H, H_c), 3.96 – 3.91 (m, 4H, H_{cod}), 2.41 – 2.15 (m, 8H, H_{cod}), 2.05 – 2.01 (m, 4H, H_{cod}). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 134.09 (C_f), 130.37 (C_g), 127.97 (C_{cod}), 79.14 (C_b), 68.14 (C_d), 63.49 (C_e), 54.70 (C_a), 51.87 (C_c), 27.90 (C_{cod}). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -32.17 (d, $^1J_{Rh-P}$ = 157.9 Hz, PTA), -144.18 (sept., ^1J = 711.2 Hz, PF_6). **ESI-MS(+)**: *m/z* 312.9192 $[M–2PF_6+Na]^{3+}$. **Elemental Analysis**: $C_{36}H_{56}Cl_2F_{12}N_6P_4Rh_2$: Calcd. C 35.99, H 4.70, N 6.99 %. Found C 34.57, H 4.73, N 6.54 %. **$S_{40°C}$** = 1.5 mg/mL in H_2O.

*4.3.3 Synthesis of the 1,3-dinuclear complex (**8**)*



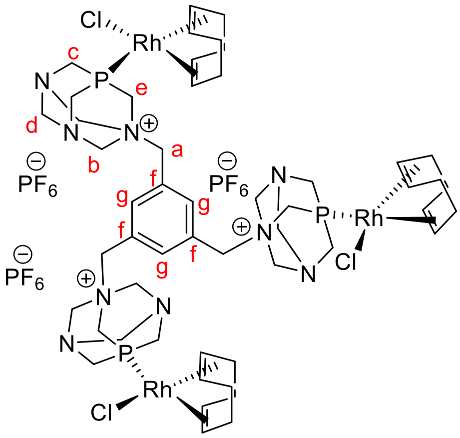
$[RhCl(COD)]_2$ (75.3 mg, 0.153 mmol) was dissolved in DCM (60 mL). Ligand **3'** (100. mg, 0.141 mmol) was then added and the reaction mixture stirred at room temperature for 20 hours with the ligand in suspension. **Yield:** 107 mg, 63 %. **M.p.:** Decomposes without melting, onset at 204.9 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.67 – 7.42 (m, 4H, ArH), 5.14 – 4.87 (m, 8H, H_b), 4.77 (d, ^2J = 11.2 Hz, 2H, H_d), 4.52 – 4.39 (m, 10H, $H_{d,cod}$), 4.31 (d, 4H, H_e), 4.22 (s, 4H, H_a), 4.04 – 3.95 (m, 8H, H_c), 2.29 (br s, 8H, H_{cod}), 2.08 – 2.00 (m, 8H, H_{cod}). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 133.63 (C_g), 131.25 (C_i), 129.99 (C_h), 128.88 (C_f), 126.31 (C_{cod}), 78.91 (C_b), 68.04 (C_d), 65.37 (C_a), 55.46 (C_e), 51.88 (C_c), 27.98 (C_{cod}). **^{31}P{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): -32.64 (d, $^1J_{Rh\text{-}P}$ = 144.5 Hz, PTA), -144.18 (sept., ^1J = 711.3 Hz, PF_6). **ESI-MS(+)**: *m/z* 312.1030 $[M{-}2PF_6{+}Na]^{3+}$. **Elemental Analysis**: $C_{36}H_{56}Cl_2F_{12}N_6P_4Rh_2$: Calcd. C 36.64, H 4.99, N 6.17 %. Found C 35.25, H 5.19, N 5.33 %. **$S_{40°C}$** = 2 mg/mL in H_2O.

*4.3.4 Synthesis of the 1,2-dinuclear complex (**9**)*



$[RhCl(COD)]_2$ (71.5 mg, 0.145 mmol) was dissolved in DCM (40 mL) after which Ligand **4'** (99.9 mg, 0.141 mmol) was added. The reaction mixture was stirred at room temperature for 20 hours with ligand **4'** in suspension. The reaction mixture was then filtered under gravity to get rid of any unreacted ligand **4'**. The filtrate was then reduced to *ca.* 10 mL and cold pentane was added to afforded complex **9** as a yellow solid which was isolated by suction filtration and dried under vacuum. **Yield:** 128 mg, 76 %. **M.p.:** Decomposes without melting, onset at 247.0 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.86 – 7.37 (m, 4H, ArH), 5.020 – 4.86 (m, 8H, H$_b$), 4.50 – 4.26 (m, 16H, H$_{d,e,cod}$), 4.09 (s, 4H, H$_c$), 3.93 – 3.90 (m, 4H, H$_{cod}$), 2.30 (br s, 8H, H$_{cod}$), 2.00 (br s, 4H, H$_{cod}$). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 135.74 (C$_g$), 131.36 (C$_h$), 127.74 (C$_f$), 126.15 (C$_{cod}$) 79.82(C$_b$), 69.86 (C$_d$), 60.51 (C$_a$), 49.89 (d, C$_e$), 45.12 (d, C$_c$). **^{31}P{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): -31.72 (d, $^1J_{Rh-P}$ = 144.2 Hz, PTA), -144.18 (sept., ^1J = 711.3 Hz, PF$_6$). **ESI-MS(+)**: *m/z* 312.1024 $[M–2PF_6+Na]^{3+}$. **Elemental Analysis**: $C_{36}H_{56}Cl_2F_{12}N_6P_4Rh_2$: Calcd. C 35.99, H 4.70, N 6.99 %. Found C 35.25, H 5.19, N 5.33 %. **S$_{40°C}$** = 2 mg/mL in H$_2$O.

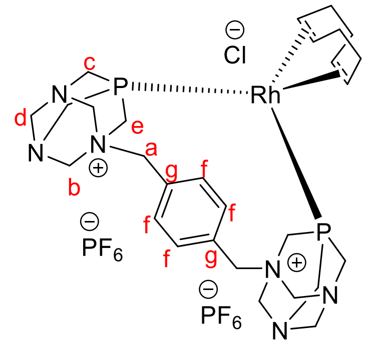
*4.3.5 Synthesis of the trinuclear complex (**10**)*



[RhCl(COD)]$_2$ (72.6 mg, 0.147 mmol) was dissolved in DCM (50 mL). Ligand **5'** (99.6 mg, 0.0973 mmol) was then added and the reaction mixture was stirred at room temperature for 24 hours. Complex **10** was observed as a yellow solid which was then isolated by suction filtration, washed with DCM and dried under vacuum. **Yield:** 105 mg, 61 %. **M.p.:** Decomposes without melting, onset at 359.4 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.72 (s, 3H, ArH), 5.31 – 5.13 (AB q, ^2J = 10.5 Hz, H$_b$), 4.77 – 4.54 (m, 12H, H$_d$), 4.48 – 4.44 (m, 18H, H$_{e,\ cod}$), 4.30 (s, 6H, H$_a$), 4.20 – 4.07 (m, ^2J = 14.5 Hz, 12H, H$_c$), 2.38 – 2.22 (m, 12H, H$_{cod}$), 2.01 – 1.91 (m, ^3J = 7.6 Hz, 6H, H$_{cod}$). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 138.33 (C$_g$), 128.45 (C$_f$), 126.89 (C$_{cod}$), 79.81 (C$_b$), 68.01 (C$_d$), 63.45 (C$_a$), 58.81 (C$_e$), 51.69 (C$_c$), 27.98 (C$_{cod}$). **^{31}P{^{1}H}**

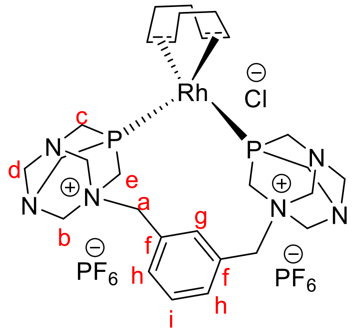
NMR (DMSO–*d*$_6$, *δ* ppm): -32.38 (d, $^1J_{\text{Rh-P}}$ = 145.5 Hz, PTA), -144.18 (sept., PF_6). **ESI-MS(+)**: *m/z* 476.9400 $[M{-}3PF_6]^{3+}$. **Elemental Analysis**: $C_{51}H_{81}Cl_3F_{18}N_9P_6Rh_3$: Calcd. C 34.74, H 4.63, N 7.15 %. Found C 33.63, H 4.97, N 8.75 %. **$S_{40°C}$** = 1 mg/mL in H_2O.

*4.3.6 Synthesis of the 1,4-mononuclear complex (**11**)*



A solution of 0.5 equivalents of the $[RhCl(COD)]_2$ dimer (70.3 mg, 0.143 mmol) in acetone (60 mL) was added dropwise to a solution of ligand **2’** (200. mg, 0.282 mmol) in acetone (20 mL). The reaction mixture was stirred at room temperature for 5 hours. The solvent was then removed and complex **11** afforded as a yellow solid which was then dried under vacuum. **Yield:** 243 mg, 90 %. **M.p.:** Decomposes without melting, onset at 214.8 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.77 (s, 4H, ArH), 5.13 – 4.97 (m, 8H, H_b), 4.84 – 4.76 (m, 4H, H_d), 4.50 – 4.45 (m, 4H, H_{cod}), 4.40 (s, 4H, H_a), 4.11 – 3.84 (m, 12H, $H_{c,e}$), 2.30 (br s, 4H, H_{cod}), 2.00 ppm (br s,H, H_{cod}). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 134.09 (C_g), 130.36 (C_f), 128.05 (C_{cod}), 79.72 (C_b), 67.97 (C_d), 63.88 (C_a), 57.85 (C_e), 51.46 (C_c), 30.18 (C_{cod}). **^{31}P{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): -32.53 (d, $^1J_{\text{Rh-P}}$ = 136.0 Hz, PTA), -144.17 (sept., PF_6). **ESI-MS(+)**: *m/z* 157.0349 $[M{-}2PF_6{-}Cl{+}Na]^{4+}$. **Elemental Analysis**: $C_{28}H_{44}ClF_{12}N_6P_4Rh$: Calcd. C 35.22, H 4.64, N 8.80 %. Found C 33.82, H 4.73, N 7.61 %. **$S_{40°C}$** = 3.5 mg/mL in H_2O.

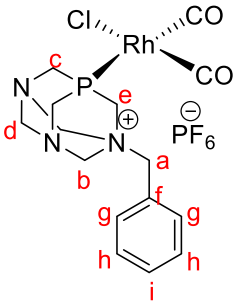
*4.3.7 Synthesis of the 1,3-mononuclear complex (**12**)*



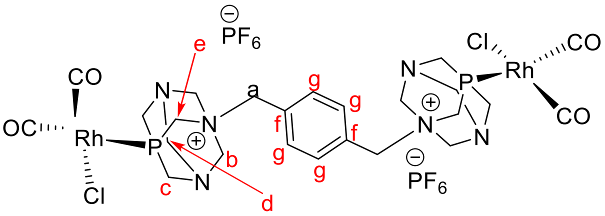
Ligand **3'** (200. mg, 0.282 mmol) was dissolved in acetone (20 mL). In a separate reaction flask, the $[RhCl(COD)]_2$ dimer (69.9 mg, 0.142 mmol) was also dissolved in dried and degassed acetone (60 mL) and the resulting solution was added dropwise to the solution of ligand **3'**. The reaction mixture was stirred at room temperature for 5 hours. The solvent was then removed under reduced pressure to afford complex **12** as a yellow solid which was then dried under vacuum. **Yield:** 236 mg, 88 %. **M.p.:** Decomposes without melting, onset at 215.6 °C. **^{1}H NMR** (DMSO–*d₆*, *δ* ppm): 7.60 – 7.54 (m, 4H, ArH), 5.19 – 4.72 (m, 12H, $H_{b,d}$), 4.49 – 4.41 (m, 4H, H_{cod}), 4.32 (d, 4H, H_e), 4.23 (s, 4H, H_a), 4.21 – 3.99 (m, 8H, H_c), 2.29 (br s, 4H, H_{cod}), 2.01 (br s, 4H, H_{cod}). **^{13}C{^{1}H} NMR** (DMSO–*d₆*, *δ* ppm): 135.20 (C_g), 133.61 (C_i), 131.20 (C_h), 130.07 (C_f), 129.73 (C_{cod}), 79.84 (C_b), 67.60 (C_d), 64.04 (C_a), 58.99 (C_e), 51.78 (C_c), 30.66 (C_{cod}). **^{31}P{^{1}H} NMR** (DMSO–*d₆*, *δ* ppm): -33.34 (d, $^1J_{Rh\text{-}P}$ = 125.6 Hz, PTA), -144.17 (sept., PF_6). **ESI-MS(+)**: *m/z* 157.0352 $[M{-}2PF_6{-}Cl{+}Na]^{4+}$. **Elemental Analysis**: $C_{28}H_{44}ClF_{12}N_6P_4Rh$: Calcd. C 35.22, H 4.64, N 8.80 %. Found C 35.31, H 5.02, N 7.93 %. **$S_{40°C}$** = 5 mg/mL in H_2O.

*4.3.8 General procedure for the synthesis of complexes **13** – **18***

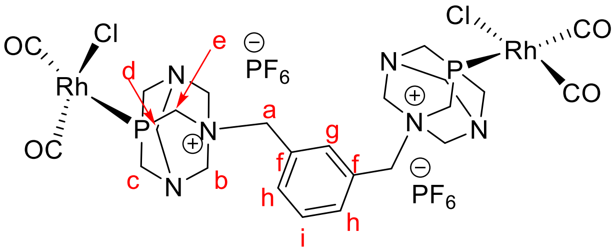
Complexes **13** – **18** were synthesised following previously reported literature procedures.[5–7] Complex **6** (51.2 mg, 0.0800 mmol), Complex **7** (200. mg, 0.166 mmol), Complex **8** (51.2 mg, 0.0800 mmol), Complex **9** (200. mg, 0.166 mmol), Complex **11** (100. mg, 0.105 mmol) and Complex **12** (100. mg, 0.105 mmol) were each dissolved in acetone (40 mL) and gaseous CO was bubbled through the solution at room temperature for 1 hour. The yellow solution gradually changed to orange. The solvent was then reduced and cold pentane added to afford Complexes **13**, **14**, **15**, **16**, **17** and **18** respectively as orange solids. The complexes were then each isolated by suction filtration, washed with pentane and dried under vacuum.



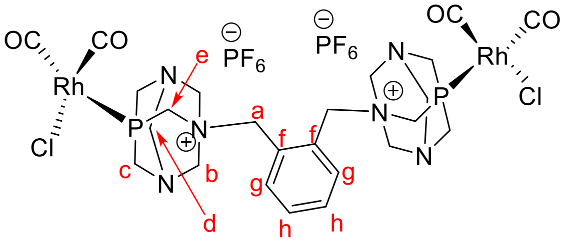
Complex 13: Yield: 32.2 mg, 70 %. **M.p.:** Decomposes without melting, onset at 147.4 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.57 – 7.49 (m, 5H, ArH), 5.15 – 5.01 (AB q, 4H, H_b), 4.79 – 4.61 (AB q, 2H, H_d), 4.42 (d, 2H, H_e), 4.25 (s, 2H, H_a), 4.13 – 3.97 (m, 4H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 192.08 (CO), 132.98 (C_g), 130.91 (C_i), 129.43 (C_h), 129.07 (C_f), 79.77 (C_b), 69.41 (C_d), 65.83 (C_a), 59.42 (C_e), 52.36 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -33.44 (d, $^{1}J_{Rh\text{-}P}$ = 125.3 Hz, PTA), -144.18 (sept., ^{1}J = 711.3 Hz, PF_6). **FT-IR:** 2048 (CO), 1996 cm^{-1} (CO). **ESI-MS(+)**: *m/z* 248.1313 $[M–PF_6+Na]^{2+}$. **Elemental Analysis**: $C_{15}H_{19}ClF_6N_3O_2P_2Rh$: Calcd. C 30.66, H 3.26, N 7.15 %. Found C 31.80, H 4.71, N 6.79 %. **$S_{40°C}$** = 4 mg/mL in H_2O.



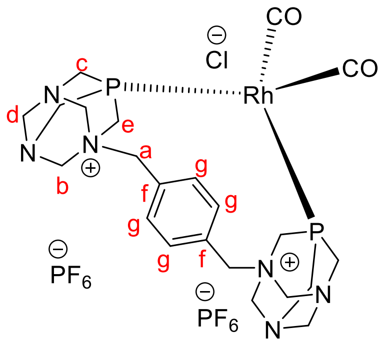
Complex 14: Yield: 178 mg, 98 %. **M.p.:** Decomposes without melting, onset at 232.8 °C. **^{1}H NMR** (DMSO–d_6, δ ppm): 7.76 – 7.62 (m, 5H, ArH), 5.19 – 5.10 (m, 8H, H_b), 4.92 – 4.73 (m, 4H, H_d), 4.45 - 4.30 (m, 8H, $H_{a,e}$), 4.21 – 4.01 (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–d_6, δ ppm): 193.77 (CO), 134.29 (C_g), 130.22 (C_f), 79.16 (C_b), 68.93 (C_d), 63.77 (C_a), 58.69 (C_e), 51.67 (C_c). **^{31}P{^{1}H} NMR** (DMSO–d_6, δ ppm): -20.93 (d, $^{1}J_{Rh\text{-}P}$ = 148.5 Hz, PTA), -144.17 (sept., ^{1}J = 711.3 Hz, PF_6). **FT-IR:** 1998 (CO), 2095 cm^{-1} (CO). **ESI-MS(+)**: *m/z* 268.1862 $[M–2PF_6+H]^{3+}$. **Elemental Analysis**: $C_{24}H_{32}Cl_2F_{12}N_6O_4P_4Rh_2$: Calcd. C 27.65, H 3.57, N 7.44 %. Found C 28.81, H 4.53, N 7.05 %. **$S_{40°C}$** = 2 mg/mL in H_2O.



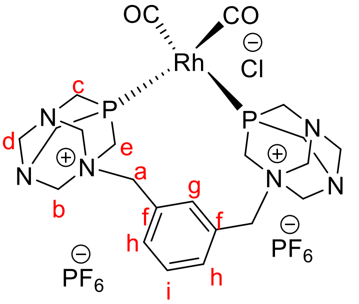
Complex 15: Yield: 64.1 mg, 73 %. **M.p.:** Decomposes without melting, onset at 228.5 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.63 – 7.46 (m, 4H, ArH), 5.11 – 5.06 (m, 8H, H_b), 4.84 (s, 4H, H_a), 4.65 – 4.43 (AB q, 4H, H_d), 4.41 – 4.01 (m, 12H, $H_{c,e}$). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 193.34 (CO), 133.60 (C_g), 131.28 (C_i), 129.99 (C_h), 129.11 (C_f), 79.25 (C_b), 69.13 (C_d), 64.64 (C_a), 56.30 (C_e), 51.89 (C_c). **^{31}P{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): -33.34 (d, $^1J_{Rh\text{-}P}$ = 125.6 Hz, PTA), -144.18 (septet, PF_6). **FT-IR:** 2075 (CO), 1996 cm^{-1} (CO). **ESI-MS(+)**: *m/z* 268.0205 $[M{-}2PF_6{+}H]^{3+}$. **Elemental Analysis**: $C_{24}H_{32}Cl_2F_{12}N_6O_4P_4Rh_2$: Calcd. C 27.65, H 3.57, N 7.44 %. Found C 28.75, H 4.32, N 6.89 %. **$S_{40°C}$** = 3 mg/mL in H_2O.



Complex 16: Yield: 175 mg, 96 %. **M.p.:** Decomposes without melting, onset at 223.5 °C. **^{1}H NMR** (DMSO–*d*$_6$, *δ* ppm): 7.57 – 7.49 (m, 5H, ArH), 5.15 – 5.01 (AB q, 4H, H_b), 4.79 – 4.61 (AB q, 2H, H_d), 4.42 (d, 2H, H_e), 4.25 (s, 2H, H_a), 4.13 – 3.97 (m, 4H, H_c). **^{13}C{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): 195.92 (CO), 135.17 (C_g), 132.71 (C_h), 128.72 (C_f), 80.00 (C_b), 71.26 (C_d), 67.57 (C_a), 58.49 (C_e), 51.46 (C_c). **^{31}P{^{1}H} NMR** (DMSO–*d*$_6$, *δ* ppm): -24.44 (d, $^1J_{Rh\text{-}P}$ = 135.7 Hz, PTA), -144.17 (sept., ^1J = 711.3 Hz, PF_6). **FT-IR:** 1996 (CO), 2051 cm^{-1} (CO). **ESI-MS(+)**: *m/z* 276.1263 $[M{-}2PF_6{+}Na]^{3+}$. **Elemental Analysis**: $C_{24}H_{32}Cl_2F_{12}N_6O_4P_4Rh_2$: Calcd. C 27.65, H 3.57, N 7.44 %. Found C 28.21, H 4.48, N 7.63 %. **$S_{40°C}$** = 3 mg/mL in H_2O.



Complex 17: Yield: 81.3 mg, 86 %. **M.p.:** Decomposes without melting, onset at 281.4 °C. **^{1}H NMR** (DMSO–*d₆*, *δ* ppm): 7.68 (s, 4H, ArH), 5.12 (m, 8H, H_b), 4.89 – 4.74 (m, 4H, H_d), 4.38 (br s, 4H, H_e), 4.28 (s, 4H, H_a), 4.12 – 4.08 (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–*d₆*, *δ* ppm): 192.83 (CO), 133.66 (C_g), 130.90 (C_f), 79.15 (C_b), 69.34 (C_d), 64.86 (C_a), 58.45 (C_e), 51.98 (C_c). **^{31}P{^{1}H} NMR** (DMSO–*d₆*, *δ* ppm): -29.32 (d, $^1J_{Rh-P}$ = 171.5 Hz, PTA), -144.14 (sept., PF_6). **FT-IR:** 1998 cm^{-1} (CO). **ESI-MS(+)**: *m/z* 188.0950 $[M–2PF_6–Cl]^{3+}$. **Elemental Analysis**: $C_{22}H_{32}Cl_2F_{12}N_6O_4P_4Rh_2$: Calcd. C 29.27, H 3.57, N 9.31 %. Found C 29.21, H 4.47, N 8.51 %. **$S_{40°C}$** = 4.5 mg/mL in H_2O.



Complex 18: Yield: 82.0 g, 87 %. **M.p.:** Decomposes without melting, onset at 281.4 °C. **^{1}H NMR** (DMSO–*d₆*, *δ* ppm): 7.70 – 7.52 (m, 4H, ArH), 5.22 – 2.03 (m, 8H, H_b), 4.86 – 4.77 (m, 4H, H_d), 4.43 (br s, 4H, H_e), 4.28 (s, 4H, H_a), 4.17 – 4.04 (m, 8H, H_c). **^{13}C{^{1}H} NMR** (DMSO–*d₆*, *δ* ppm): 193.46 (CO), 135.20 (C_g), 133.25 (C_i), 131.20 (C_h), 130.32 (C_f), 79.85 (C_b), 68.15 (C_d), 64.03 (C_a), 58.39 (C_e), 51.69 (C_c). **^{31}P{^{1}H} NMR** (DMSO–*d₆*, *δ* ppm): -28.10 (d, $^1J_{Rh-P}$ = 171.5 Hz, PTA), -143.95 (sept., PF_6). **FT-IR:** 1996 cm^{-1} (CO). **ESI-MS(+)**: *m/z* 188.0943 $[M–2PF_6–Cl]^{3+}$. **Elemental Analysis**: $C_{22}H_{32}Cl_2F_{12}N_6O_4P_4Rh_2$: Calcd. C 29.27, H 3.57, N 9.31 %. Found C 29.20, H 4.40, N 8.65 %. **$S_{40°C}$** = 6 mg/mL in H_2O.

4.4 General procedure for the hydroformylation reactions

The hydroformylation reactions were carried out in a 90 mL stainless steel pipe reactor. The reactor was charged with toluene (5 mL), distilled water (5 mL), the substrate, 1-octene (805 mg, 7.18 mmol), the internal standard, n-decane (204 mg, 1.44 mmol) and either one of the Rh-PTA catalyst precursors **6** - **18** (2.87 x 10^{-3} mmol, with respect to the metal centre, i.e. Rh:substrate = 1:2500). The air-tight reactor was de-aerated by flushing three times with nitrogen gas and then twice with syngas, then pressurised and heated to the desired syngas ($CO:H_2$, 1:1) pressure and temperature respectively. After 8 hours, the reactor was depressurised and the organic layer decanted and analysed using a Varian CP-8400 GC instrument. Leaching studies were conducted using an ICP-OES Varian 750-ES spectrophotometer.

4.5 References

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Chapter 5

Summary and Future work

5.1 Overall summary

A series of mono-, di- and trimeric alkylated PTA ligands (**1’** – **5’**) were synthesised. These ligands were then reacted with the dimeric rhodium precursor $[RhCl(COD)]_2$ to afford the corresponding mono-, di, and trinuclear Rh(I)-PTA complexes (**6** – **12**). In addition, the carbonyl analogues (**13** – **18**) were synthesised by reacting each of the mono- and dinuclear COD complexes **6** – **12** with carbon monoxide. The ligands were found to be water-soluble at room temperature and the complexes were found to be water-soluble at elevated temperatures. The ligands and complexes were characterised using various spectroscopic and analytical techniques. All complexes are air stable at room temperature. The complexes were then used as catalyst precursors in the aqueous biphasic hydroformylation of 1-octene.

All complexes proved active as catalyst precursors in the hydroformylation of 1-octene with the COD complexes (**6** – **12**) displaying better conversion of 1-octene. All complexes displayed good chemoselectivity for aldehydes, with the COD complexes (**6** – **12**) displaying better chemoselectivity for aldehydes than the CO complexes (**13** – **18**). Moreover, the CO complexes (**13** – **18**) displayed better regioselectivity for linear aldehydes than the COD complexes (**6** – **12**). The activity and selectivity of the catalyst precursors were greatly influenced by the difference in electronic properties between the COD and CO ligands. The CO ligand is a strong π-acceptor and can therefore lead to greater back-donation of electron density from the metal centre resulting in the strengthening of the Rh–C bond, thus making it difficult for the CO ligand to dissociate leading to a delay in the formation of the active species in comparison to the COD complexes.

Studies conducted at different time intervals showed that the trinuclear complex (**10**) displays a faster catalytic rate than the dinuclear complexes (**7** – **9** and **14** –**16**) which, in turn, exhibit a faster rate than the mononuclear complexes (**6**, **11** – **13**, **17** and **18**). Catalyst recyclability was simplified by using water as one component of the reaction media. The water layer was easily separated from the organic layer containing the products by decantation. The catalysts could be recycled three times with a decrease in the conversion of 1-octene after each run for each catalyst precursor. Leaching studies showed a significant loss of the metal complexes (*ca.* 90 %) into the organic layer after each catalytic run, accounting for the drastic decrease in conversion.

Mercury poisoning studies were conducted and confirmed that, under the catalytic conditions, all complexes (**6** – **18**) behave entirely as homogeneous catalysts when evaluated as catalyst precursors for the aqueous biphasic hydroformylation of 1-octene.

5.2 Future outlook

This work has shown that catalyst design is of importance in improving the rate, activity and selectivity of the hydroformylation reaction. Despite the facile separation of the catalyst-containing aqueous layer for recycling, the recyclability results were not encouraging. The poor solubility of the complexes in water is the main reason for these poor results. Future studies may involve designing complexes that contain uncoordinated PTA moieties so as to increase the water-solubility of the catalyst precursors. Furthermore, a suitable organic solvent that the catalyst precursors are not soluble in even at elevated temperatures and pressures could be used to avoid loss of the complexes into the organic layer. In addition, more studies need to be conducted to determine the mechanism of the catalytic reactions in order to fully understand the catalytic cycle and thus assist in the fine tuning of catalyst precursors used under aqueous biphasic conditions.